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Facing educational Challenges in Molecular Life Science – A Thesis to reconstruct Cell Membrane Biology for Upper Secondary Teaching and Learning

Leonie Isabelle Johann

THE FACULTY OF EDUCATION AND ARTS

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Preface

This thesis is submitted in fulfilment of the requirements for the degree of *philosophiae doctor* at Nord University within the PhD programme *the study of professional praxis*. The research presented here is conducted under the supervision of Fredrik Rusk, affiliated with the Faculty of Education and Welfare Studies at Åbo Academy, Finland and the Department of Teacher Education at Nord University, Bodø, and Jorge Groß, affiliated with the Department of Science Education at Otto-Friedrich-University of Bamberg, Germany. The thesis builds on the *kappe*[1] document at hand and a collection of three journal articles, presented in chronological order at the end of this kappe document. One of these articles is published, one is accepted for publication and the third is submitted for publication. I am the only author of this kappe document and the main author of all articles, with my supervisors functioning as co-authors in all articles. Article I is furthermore joint with Denis Messig, affiliated with the Department of Science Education at the Otto-Friedrich-University of Bamberg, while article III is joint with Michael Reiss, affiliated with the Institute of Education at University College London, England.

To write the final words of my thesis after three years full of expected, and even more unexpected, challenges, surprises and moments of delight is almost surrealistic. There is so much I was not prepared for when embarking on this PhD journey. To write a thesis has more than expected been a lonely process where I especially got to know myself in all its shades. This loneliness was certainly not helped by the COVID-19 pandemic, which hit me as all other people unprepared, and disabled my dreams of visiting exciting conferences, seminars and not least Michael Reiss' research group in London. Despite the challenges I had to tackle on the way of, hopefully, becoming a scholar, I answered my mother's questions unhesitatingly with a certain *yes* when she

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[1] To increase readability, italicisation is only used for first usage of key terms. It is furthermore occasionally used to put emphasis on single words.

asked me if I would once again decide to conduct my PhD. Especially in times of global challenges, as illustrated by COVID-19, I feel extremely privileged having received the chance to really follow my own research interests and motivations.

Conducting this thesis is a process I would have never been able to achieve on my own. There are many people who in different ways have helped me along the way. First of all, I want to thank the participating students and teachers who with their commitment in the form of honest and authentic behaviour and motivation made my research possible in the first place. It has been a pleasure for me to participate in real classroom lessons and attempt to reconstruct students' understanding and not least engage in discussions with them about the usefulness of education.

I want to thank Fredrik who had the responsibility and courage to jump in as my main supervisor when my PhD-project had already progressed for a year or so. With your unagitated habits of being, your deadpan humour, your good analytical sense and expertise about educational research and practice you have helped me not to lose my nerves completely (just sometimes) and to continuously remind myself of the big questions such as where and what I want to accomplish with my study. Thank to Jorge, my co-supervisor from Germany who has contributed with his didactical spirit in the form of sound expertise on the processes of educational reconstruction. He was never tired of a) reading up on the Scandinavian ways of organising a PhD, which are different to German ways, and b) encouraging me to believe in myself and my research.

I also want to thank the skilful supervisors and organisers from the research school of NAFOL. With their humour and genuine care for my, and my research fellows', wellbeing during COVID-19 they have contributed to shaping a unique atmosphere between us participants, thus greatly contributing to the conduction of my thesis. I further want to thank the research groups of which I am a part, namely the *Didaktiker* in Bamberg, and the groups *læring i interaksjon* and *praktisk kunnskap* in Bodø, for reading my texts and providing useful and skilful feedback. I furthermore thank Kåre Haugan and especially Magdalena Kersting for being critical, constructive and not least encouraging opponents in interim evaluation seminars. I am in this regard very grateful that you, Clas Olander and Lena Tibell have so swiftly agreed upon functioning as my 1st and 2nd opponent respectively. Lena's research was one of the inspirations that fuelled my motivation to conduct this thesis in the first place.

I want to thank my good friends who never stopped encouraging me in my processes of carrying out this PhD even though I sometimes felt like giving up. A warm and hearty thanks goes moreover to my great PhD colleagues from Nord University, Tone, Elin and Jannike, and especially Camilla and Julie. We have laughed and cried together; we have shared moments of frustrations and happiness; we have discussed professional content, and even more often not. Julie, thank you for your small, big gestures which always made me feel welcome when I came home after a journey, your genuine care, and for becoming a friend to me. Camilla, a warm thank you for sharing your peanut butter with me, for reading my texts critically, for working in the night with me, laughing at and with me, and becoming my friend.

Least, but definitely not last, I want to thank my family. Even though mostly separated by thousands of kilometres, my mother and my father, Heike and Klaus, along with my brothers, David and Dominik, have never lost their faith in me. They have provided great care, stability, safety and belonging, tackled my itchiness and never given up upon me. They always had an open ear for my concerns, and when being together, provided me with food and many hugs. A great thanks also goes to my nephews Emil and Alexander who always make me laugh and remind me of the important things in life.

Bodø, December 2021

Leonie Johann

Abstract

This compilation thesis consisting of three individual articles and one kappe document proposes an empirical- and theory-based educational reconstruction of cell membrane biology (CMB) for the upper secondary level. To look at the rapidly evolving scientific theory of CMB through educational lenses is highly relevant because it is constantly becoming more abstract for non-experts, while at the same time influencing many aspects of our everyday life. Understanding the molecular mechanisms of biological processes in cell membranes informs, amongst others, the development of technological applications, such as vaccines against COVID-19, and influences peoples' personal and social health decisions. As a growing need for education in this theory and the emerging field of molecular life science (MLS) in general has been recognised worldwide, major challenges remain to identify suitable educational approaches to transcend existing MLS theories into subject areas accessible for teachers and students at the upper secondary level.

Even though existing research has started to look at CMB from the viewpoint of education, investigational efforts often regard the advanced tertiary level. Moreover, there is a scarcity of research that looks at the interplay of students' conceptions, aspects of content selection and teaching design. To propose fruitful teaching and learning strategies that are applicable on the upper secondary level and in the context of increasing societal challenges, there remains a need to systematically approach CMB education within an interdisciplinary and holistic educational framework.

This thesis aims to address this need by means of employing the Model of Educational Reconstruction (MER) as constructivist-orientated practical framework for lesson planning and links it with revised *conceptual change* learning theories and *experiential realism* as a cognitive linguist theory for understanding. These lines of research are pursued in the three articles with each of their sub-aims and research questions and deepened by a synthesis in this kappe document. Positioned in the realms of an interpretive research paradigm, data has been collected through qualitative content analysis (QCA) of relevant scientific literature in the field of CMB to systematically analyse and identify scientific core ideas from the viewpoint of upper secondary education. Furthermore, individual interviews (n=9) and two teaching experiments in classroom-similar settings were conducted to collect and identify upper secondary biology students' conceptions and study their learning processes while working with specifically designed learning activities. Throughout the analytic processes, specific emphasis has been put on understanding students' and scientists' respective conceptions within their social and cultural discourses by means of at looking at their idiosyncratic usage of language.

On a general basis, the integrated findings of my research demonstrate the applicability of the MER as practical theory to inform contemporary biology education research by means of putting emphasis on the contingency of scientific and student ideas and their mutual influence. Outcomes of the thesis suggest *compartmentalisation* and *multicellular coordination* in the context of functional processes on the evolutionary and organism level as essential scientific core ideas for upper secondary education. Emphasising the interrelation of these levels seems particularly important because students—in lack of necessary concrete everyday experiences—are found to have difficulties grasping how biological systems can be enclosed and at the same time dynamically organised and open to their environment. To counteract students' lack of experiences and bridge between cognitive and affective domains of learning, this PhD-project suggests analogies as an overall teaching strategy to inform the design of multiple visual teaching tools. To employ this educational strategy fruitfully, it seems however crucial to consider the interplay of a multitude of factors, namely the design of teaching tools, students' ability to understand them, and scaffolding by cooperative learning environments supporting dialogic conversations.

The significance of this thesis is that it provides relevant and unique insights into processes of educational reconstruction on a new scientific topic within a key field of science in the 21st century. In doing so, it creates awareness about the unique responsibility of biology education to educate students in a way that allows them not only to make informed decisions regarding personal and social health issues, but also think of humans as *one* species amongst many others. The knowledge produced has theoretical and practical implications with regard to many aspects of modern biology education. Reasons and content for modern biology education and their practical implementation in educational settings are proposed, and suggestions are made with regard to the organisation of biology curricula, biology teacher education and professional development.

Norsk sammendrag

Denne artikkelbaserte avhandlingen, bestående av tre enkeltartikler og ett kappedokument, presenterer en empiri- og teoribasert didaktisk rekonstruksjon av cellemembranbiologi (CMB) for videregående opplæring. Å se på CMB med et didaktisk blikk er høyst relevant fordi denne vitenskapelige teorien utvikler seg raskt og blir dermed mer og mer abstrakt for ikke-eksperter samtidig som at den påvirker mange aspekter i hverdagen vår. Å forstå molekylære mekanismer av biologiske prosesser i cellemembran har blant annet innflytelse på utviklingen av nye teknologier og økt innsyn i hvordan sykdommer oppstår. Et dagsaktuelt eksempel er vaksine mot COVID-19, eller det kan være beslutninger som tas på individ -og samfunnsnivå når det gjelder helse og livsstil. Pedagoger, forskere og beslutningstakere nasjonalt og internasjonalt har begynt å erkjenne et voksende behov for utdanning i denne teorien og det raskt ekspanderende feltet molekylærbiologi (MB) generelt. Til tross for dette, gjenstår store utfordringer med å finne didaktiske tilnærminger egnet til å omdanne abstrakt MLS- innhold til innhold som er tilgjengelig for lærere og elever i videregående opplæring.

Selv om eksisterende forskning har kastet lys på CMB fra et didaktisk ståsted, er forskningen ofte knyttet mot avansert undervisning på universitetsnivå. Det er dessuten få studier som ser på samspillet mellom elevforestillinger, aspekter som gjelder utvalg av innhold til læreplanen og undervisningsdesign. For å finne lærings- og undervisningsstrategier som er anvendelig i videregående opplæring og i en samfunnskontekst, er det et resterende behov for en systematisk tilnærming til CMB innenfor et tverrfaglig og helhetlig didaktisk rammeverk.

Denne avhandlingen har som mål å møte dette behovet ved å anvende modellen for didaktisk rekonstruksjon (MDR) som en konstruktivist-orientert praktisk teori for undervisningsplanlegging, og forbinder denne med reviderte *conceptual change-*

teorier og *experiential realism* som en kognitiv-lingvistisk-basert forståelsesteori. Basert på dette teoretiske rammeverket belyser de tre artiklene hver sine delmål og forskningsspørsmål som er utdypet i en overordnet syntese i denne kappa. Posisjonert i et fortolkende paradigme, er data samlet inn ved å anvende kvalitativ innholdsanalyse (KIA) av relevant vitenskapelig CMB litteratur. Dette er brukt som grunnlag for å systematisk analysere og å identifisere vitenskapelige kjernekonsept med utgangspunkt i videregående opplæring. Videre, er individuelle intervju (n=9) og to *teaching experiments* i klasseromslignende settinger gjennomført. Formålet har vært å samle inn, identifisere og tolke biologielever i videregående opplæring sine forestillinger og læringsprosesser mens de jobber med spesialdesignede læringsaktiviteter. Gjennom hele analyseprosessen er det lagt spesielt vekt på å forstå elevenes og forskernes respektive forestillinger innenfor deres sosiale og kulturelle diskurs ved å undersøke deres bruk av språk.

På et generelt plan viser mine integrerte funn anvendeligheten av MDR som praktisk teori for å drive med moderne biologididaktisk forskning ved å legge vekt på likeverdigheten av forskernes og studentes forestillinger og deres gjensidig inflytelse. Funnene fra denne avhandlingen foreslår *kompartmentalisering* og *multicellulær koordinasjon* i en kontekst av funksjonelle mekanistiske prosesser på organisme- og evolusjons-nivå som sentrale vitenskapelige kjerne konsept i videregående opplæring. Å legge vekt på samspillet mellom disse nivåene ser ut til å være kritisk fra et didaktisk synspunkt: I mangel av nødvendige konkrete hverdagserfaringer ser elevene ut til å ha problemer med å forstå hvordan biologiske systemer kan være lukket, men samtidig dynamisk organisert og åpen mot deres omgivelser. For å tilby nye erfaringer og bygge bru mellom kognitive og affektive domener av læring foreslår denne avhandlingen analogier som overordnet undervisningsstrategi for å designe ulike visuelle undervisningsverktøy. For å anvende denne strategien på en fruktbar måte ser det riktignok ut som at det er viktig å ta høyde for samspillet mellom ulike faktorer, som design av verktøyene, elevenes evne til å forstå dem og en generell innramming av undervisningsopplegg som fremmer dialog.

Avhandlingen presenterer relevant og unik innsikt i didaktiske prosesser innenfor et nytt område som er knyttet til ett av det 21. århundrets naturvitenskapelige kjerneområder. Dermed bidrar avhandlingen til oppmerksomhet rundt det unike ansvaret biologiundervisningen har: Å danne og utdanne elever på en måte som fører til at de evner å ta kunnskapsbaserte valg for seg selv og andre (knyttet til for eksempel egen og andres helse), men også til å tenke på mennesker som *en* blant mange andre arter. Denne avhandlingens kunnskapsbidrag har teoretiske og praktiske implikasjoner for flere aspekter av framtidas biologiundervisning. Det gjelder både begrunnelse for innholdet og praktisk gjennomføring av fremtidas biologiundervisning, innspill til utforming av læreplaner, og forslag til (etter)utdanningen av biologilærere.

Register of abbreviations

The following abbreviations are used in the thesis:

CMB	Cell Membrane Biology
COVID-19	Coronavirus disease of 2019
DBR	Design-based research
EARLI	European Association for Research on Learning and Instruction
MER	Model of Educational Reconstruction
MLS	Molecular Life Science
NAFOL	Norwegian National Research School in Teacher Education (Nasjonal forskerskole for lærerutdanning)
NFSUN	Nordic Research Symposium on Science Education (Nordisk Forskersymposium om Undervisning I Naturvitenskap)
NSD	Norwegian Centre for Research Data (Norsk senter for forskningsdata)
PhD	Doctor of Philosophy (Philosophiae Doctor)
QCA	Qualitative Content Analysis

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List of original articles

The thesis consists of the following original articles, which I refer to by their Roman numerals (I-III).

Article I

Johann, L., Groß, J., Messig, D., & Rusk, F. (2020). Content-Based and Cognitive-Linguistic Analysis of Cell Membrane Biology: Educational Reconstruction of Scientific Conceptions. *Education Sciences*, *10*(6), 151.

Article II

Johann, L., Groß, J., & Rusk, F. Towards Understanding the Learning Challenges of Cell Membrane Biology—An Interview Study to Explore the Genesis of Students' Conceptions. Manuscript submitted to *International Journal of Science and Mathematics Education*.

Article III

Johann, L., Rusk, F., Reiss, M., & Groß, J. Upper secondary students‘ thinking pathways in cell membrane biology—an evidence-based development and evaluation of learning activities using the Model of Educational Reconstruction. Accepted for publication by *Journal of Biological Education*

Part I

1 Introduction

During the last decades, MLS has evolved as a key field of scientific and technological innovation with sound impact on many aspects of our daily life. These range from the introduction and acceptance of new technologies and drugs, to health-and sustainability related questions on the societal and personal level (Bell, 2001; Mc Ewen, 2021; Tibell & Rundgren, 2010). While the societal importance of knowledge produced in MLS is constantly growing, so does its abstract and interdisciplinary character. These developments combined have provoked educational concerns throughout the world: Science educators and policymakers globally (Bayerisches Staatsministerium für Unterricht und Kultus, 2004; Mc Ewen, 2021; Mohlhenrich, 2021; Verhoeff et al., 2008) and locally in Norway (Gregers & Suhr Lunde 2021; Utdanningsdirektoratet, 2021a, 2021b) have recognised an increased need to offer appropriate school education and information that allows students and the general public to become well-informed citizens actively taking part in discussions about MLS. However, especially on the upper secondary level, educational challenges remain; these regard amongst others the selection of adequate core concepts as well as teaching strategies in order to promote learning processes regarding the nature of a given MLS concept rather than the memorisation of a large number of unrelated facts (Howitt et al., 2008; Van Mil et al., 2013).

Rooted in the PhD programme the study of professional praxis, this PhD-thesis addresses these developments and challenges by means of theoretically and empirically exploring how the abstract and important scientific theory of CMB can be turned into a more accessible subject area that can be taught and learnt at the upper secondary level. CMB presents an exciting scientific and educational topic within the field of MLS because it explores the molecular processes that dynamically establish a separation between the interior of an organism and its outside (Watson, 2015). Understanding the scope of these processes provides us with critical insights into the genesis of a number of human diseases, such as many cancer types, but also the genesis of life itself.

Despite its scientific and societal relevance, there are rather few research-based attempts of bringing CMB to upper secondary classrooms. Existing literature mainly examines other MLS topics and sub-fields like genetics (e.g., Duncan & Reiser, 2007; Lewis & Kattmann, 2004; Marbach-Ad & Stavy, 2000), explores teaching and learning CMB at the rather advanced university level (Christianson & Fisher, 1999; Michael & Modell, 2019; Rundgren et al., 2010), or respectively focuses on subcellular transport processes at cell membranes (Hasni et al., 2016) without giving much attention to linking these to the other levels of biological organisation. Furthermore, studies often employ designs where students' conceptions seem little considered both in the processes of selecting and teaching core concepts of CMB.

The lack of existing research along with students' persistent learning difficulties in the general field of MLS (Duncan & Reiser, 2007; Tibell & Rundgren, 2010; Verhoeff et al., 2008) justify an interdisciplinary student-orientated approach as employed in this thesis. Theoretically framed by the MER (Duit et al., 2012) as a practical constructivist model for lesson planning, revised conceptual change approaches (Duit & Treagust, 2003; Vosniadou et al., 2008) and experiential realism (Gropengießer, 2007; Lakoff & M. Johnson, 1980) as a cognitive-linguist theory for understanding, this thesis acts on the assumption that existing scientific theories have to be reconstructed for educational purposes by means of considering students' conceptions in the processes of lesson planning *and* teaching. This is due to the fact that learning is sustained as a process of actively developing existing conceptions in line with understanding the meaning of socially and culturally shared concepts (Riemeier & Gropengießer, 2008; Treagust & Duit, 2008a). Conceptions in this thesis are understood as individual, dynamic mental models that structure and interpret the bodily and social experiences we make in our everyday lives (Driver, 1989; Gropengießer, 2001). Since abstract phenomena like cell membranes, but also everyday concepts like *love* or *time*, are beneath our perception, we lack concrete experiences with them and can therefore not directly understand, but only imagine them. Our imagination, a metaphorical understanding of one concept in terms of another (Lakoff & M. Johnson, 1980, 1999), becomes visible in the language we employ. Language in this thesis is thus conceived as a crucial tool to both visualise and shape our conceptions (Gropengießer, 2007; Lakoff & M. Johnson, 1980), in terms of verbal as well as all kinds of visual symbols such as depictions, drawings, schemes, chemical formulae, or physical models (Harrison & Treagust, 2000; Lemke, 1990). In regard to these considerations, this thesis is specifically concerned with exploring how the interplay of experiences, conceptions and language contributes to learning and teaching CMB.

Both the MER (Duit et al., 2012; Kattmann et al., 1997) and some MLS researchers (e.g., Trujillo et al., 2015; Van Mil et al., 2013) emphasise that the process of transcending existing scientific theories into content for schooling means to understand the given theories on the basis of idiosyncratic scientific processes, developments and modes of thinking. In the further course of this introduction chapter, I therefore provide rationales and contexts for the field of MLS education by means of tracing the historical developments and characteristics of biology as the main reference discipline of MLS before I briefly present the scientific theory of CMB within the context of MLS. I subsequently contextualise my thesis within the broader science and biology curricula developments that have taken place under the increasing influence of constructivist notions during recent decades, with particular attention paid to Norwegian developments which provided the setting for the data collection in this thesis. A presentation of the combined motives of this PhD-project and how these inform its overall aim and research questions round off this chapter.

1.1 Background: Rationales and contexts for molecular life science education

1.1.1 Molecular life science as a key scientific discipline of the 21st century

In the following, I present biology (Greek: *bíos* = life; *lógos* = word, knowledge, teaching) as a scientific discipline that differs from other sciences in terms of dealing with the study of life (Mayr, 1961/2004), and which, perhaps more than any other science, has been subject to tremendous technological and conceptual advances in the last two centuries (Kafatos & Eisner, 2004; Mc Ewen, 2021; Mohlhenrich, 2021).

Historically, biology as the study of living matter has been lagging behind chemistry and physics —apparently because studying organisms is much more complex than studying inanimate matter (Carroll, 2019; Pearce Williams, n.d.). The beginning of biology as an independent discipline with equal rights as chemistry and physics is in general prescribed to such landmarks as Darwin's theory regarding the origin of species in 1859, Schwann's and Schleidens' cell theory in 1838 or Mendel's pea experiments in 1865 where he discovered the fundamental laws of inheritance (Lombard, 2014). Nevertheless, it is the 20th century that is widely regarded as the century of biology (Kafatos & Eisner, 2004). This is amongst other reasons due to the invention of pioneering technologies, for example, X-ray crystallography or electron microscopy, which finally allowed biologists to get a glimpse of both sub-cellular structures and processes (such as molecules and organelles, e.g., nucleic DNA, and the processes of protein synthesis at ribosomes). Due to the limited resolution of light microscopes, biologists' study of life was historically limited to cells, and their nucleus as the sole subcellular structure. Consequently, teleological explanations, where structures were ascribed to serve the purpose of function, had dictated the thought of biologists and scientists in general until the beginning of the 20th century (Schultz, 2002). Galen, for example, a Greek physician, surgeon and philosopher who had practiced around 150 A.D. described according to Temkin (1973) the blood circulation as follows:

> All parts of the human body are formed in the optimal manner to serve their intended human purposes. Nature is provident, just, and all knowing and does nothing in vain (p. 167).

In regard to these historical developments of science and biology, the discovery of the molecular level turned out to be the missing link, it provided “unity in biological phenomena” (Duncan & Boerwinkel, 2018, p. 36). By answering why- and how-questions (Mayr, 1961/2004; Van Mil et al., 2016) it enabled biologists to understand that in fact most biological processes are neither idiosyncratic for particular species, they rather account for all species, nor are they idiosyncratic for the different levels of biological organisation. The latter refers, to the in biology, traditional distinction of hierarchical levels—such as the biosphere, ecosystems, bioscenos, the organism, organ systems, tissues, cells, organelles and molecules as a means to identify parts, and processes, and relate these to each other (Hammann, 2019; Schneeweiß & Gropengießer, 2019). In addition to linking what has formerly been strictly separated biological disciplines, modern biology also links different disciplines, because in their nature, molecular structures and function are driven by the laws of chemistry and physics. When furthermore combined with applied disciplines, for example, medicine or agriculture, modern biology is then generally called MLS (Tibell & Rundgren, 2010); it answers questions as to how to develop effective COVID-19 vaccines or herbicide-tolerant crops. Although also other sciences have a sound impact on peoples’ daily life, modern biology is asserted to have an “even more direct and dramatic, and personal impact” by means of influencing the “acceptance or rejection of technological advances, including vaccinations, genetically modified foods and gene therapies, and, on the personal front, the reasoned evaluation of product claims and lifestyle choices” (Klymkowsky et al., 2003, p. 155).

With the rapidly increasing scientific knowledge stemming from sub-disciplines, for instance proteomics, the large-scale study of proteins, and the study of membrane lipids, CMB is a crucial theory within MLS (Lombard, 2014; Nicolson, 2014; Watson, 2015). It enables scientists to gain a deeper understanding of how cells (as parts of organisms or organisms themselves) govern homeostasis, that is, how they balance their internal environment in relation to their surrounding external environment by continuously exchanging matter—one of the proposed key features of life aside from cell division, growth, metabolism and development (von Bertalanffy, 1968). In multicellular organisms such as humans, external environments refer both to tissue environments, that is, neighbouring cells (of the same cell type) and their secretions, as well as the outer environment, which is not part of an organism. Often, stimuli from the outer environment, for example, radiation, can disrupt homoeostasis in internal environments, leading to the state of disease. For example, mutation of genetic coding for specific membrane proteins can cause an overexpression of membrane proteins (more proteins are produced than there naturally should be). Since membrane proteins are crucial regulators of many cell functions, including communication with other cells, the overproduction of membrane proteins can lead to a state of uncontrolled cell division (the hallmark of cancer cells) (Almén et al., 2009; Kampen, 2011).

In a nutshell, technological advances along with increasing interdisciplinarity has advanced MLS to a key scientific discipline in facing the societal challenges of the 21st century. As will be outlined in the next section, it can seem that despite its societal relevancy, school curricula worldwide have only recently started to fully recognise the educational responsibilities, challenges and potentials that lie in the interdisciplinary and abstract character of MLS.

1.1.2 Molecular life science in the realm of historical and recent curriculum developments

Until the 1960s the main aim of school science was to educate future scientists by means of transferring a simpler version of scientific knowledge to students (DeBoer, 2014; Sjøberg, 2009). This tradition of viewing learners as passive receivers of knowledge can, on the one hand, among other things be traced back to learning theories like behaviourism[2] and, on the other, positivism. Postulating that knowledge arises directly from experienced things rather than being a human construction, the latter had been one of the predominant paradigms within which scientists had carried out their inquiries for centuries (Sjøberg, 2009; Taylor, 2014). Due to the growing influence of constructivist ideas—most famously propagated through Piaget's developmental studies on the behaviour of children (around 1920s)—resistance against this kind of educational view grew in Western culture[3] amongst scientists and the general public (DeBoer, 2014; Jorde & Dillon, 2012; Sjøberg, 2009). Subscribing to the view that learners construct knowledge on the basis of the already known instead of passively receiving knowledge, pedagogues (e.g., Klafki, 1969), scientists (e.g., Wagenschein in the 1960s and Whitehead in the beginning of the 20th century) and psychologists (e.g., Bruner's cognitive theories on learning in the 1960s) were in unison demanding for a revolution in science curricula organisation. They asserted that science curricula should cover fewer, but more critical, general ideas rooted in students' minds in order to make science relevant for the everyday life of *all* students rather than a few experts (Bailey & Olson, 2014; DeBoer, 2014). This demand was particularly emphasised in biology education: Traditionally dealing with the investigation of different species by means of step-by-step moving upwards from single-cellular organisms to humans (Wagenschein, 1968/1999), biology as a school discipline has more than any other school science discipline faced the challenge of an enormous abundance of content. This abundance has challenged educators and students alike to select general ideas (Weber, 1967), on the one hand, and abandon rote-learning strategies on the other.

With the rapidly produced knowledge in modern biology, these challenges remain grand challenges of contemporary biology education (Çimer, 2012; McComas et al.,

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[2] Popularly advocated by psychologists such as Skinner (1904-1990), behaviorism is a theory of learning based on the main idea that conditioning can shape all kinds of behavior and that, thus, our actions can be shaped as responses to environmental stimuli.

[3] Western culture in this context mainly refers to Europe and the USA, which have had similar science curricula developments.

2016). Moreover, biology education must grapple with problems such as a lack of interest from the students' side (Schreiner & Sjøberg, 2004), which even appears to diminish with age (Prokop et al., 2007), the subjects' perceived difficulty amongst students (Bahar et al., 1999; Çimer, 2012) and the education of skilled biology teachers (McComas et al., 2018). On top of these more general educational challenges, Tibell and Rundgren (2010) claim in their overview over developments, trends and literature in MLS education that this field faces further unique challenges. These challenges, which will be outlined in more detail in chapter 2, are asserted to regard amongst others the identification of adequate core concepts and instructional tools to visualise the abstract content in a way that is understood by students. Furthermore, challenges are tied to the organisation of school curricula across the world such as, for example, mistreatment of its interdisciplinary character (Duncan & Reiser, 2007; Howitt et al., 2008; Verhoeff et al., 2008).

In Norway, MLS content, mainly part of the upper secondary curriculum, is indeed scattered to courses in physics (e.g., energy conversation), chemistry (e.g., the chemistry of polar and nonpolar substances, and the structure of lipids and proteins), and two distinct biology courses, available for students at the 12th and 13th level. Until August 2021, upper secondary biology curricula were furthermore for the most part organised traditionally according to a distinction on the cellular level between eukaryotic and prokaryotic cells and a distinction according to the different levels of biological organisation, like cell biology and human physiology (Utdanningsdirektoratet, 2020). However, in response to increasing societal challenges, the Norwegian upper secondary biology curriculum has recently undergone sound revisions in the context of general national curricula school reforms. In line with the introduction of three interdisciplinary topics concerning key social challenges, namely *health and life skills*, *democracy and citizenship* and *sustainable development*, key features of the reform are an increased emphasis on practical and exploratory issues and a clearer focus on core elements (Utdanningsdirektoratet, 2021b). The contribution of upper secondary biology education to these interdisciplinary topics is formulated as a means to provide students with competencies so they can, amongst others, make informed decisions regarding their own health, consider ethical questions regarding biotechnology or sustainability and how human activity affects other life on earth (Utdanningsdirektoratet, 2021c). The new core elements in upper secondary biology regard *biological systems* as the relation between the different levels of biological organisation; *biological processes* as the differentiating of cells, tissues and physiological processes; *practices in biology* as the use of models; and *biology in society* as concerning societal challenges related to health, environmental and food production issues. These core elements are linked to competency aims that more precisely formulate learning outcomes; students are, for example, supposed to investigate relations between cell structures and functions and make an account of how cell membranes are the basis for intercellular communication or demonstrate how selected regulating mechanisms govern human homeostasis and explore how lifestyle choices can affect these mechanisms (Utdanningsdirektoratet, 2021a).

In the realm of the above outlined Norwegian curriculum developments which seem in line with what (biology) curricula emphasise internationally (e.g., Lehrplan 21, 2016; McComas et al., 2018; Mohlhenrich, 2021), the terms deeper learning (Norwegian: dybdelæring) (Moksnes, 2020; Pellegrino & Hilton, 2012) and conceptual learning/understanding have gained increasing weight (cf. Gregers & Suhr Lunde, 2021; Konicek-Moran & Keeley, 2015), albeit there is no clear consensus in the educational community regarding their meaning (Anderson & Schönborn, 2008; Moksnes, 2020; Schönborn & Anderson 2008a). Since this thesis is, as mentioned introductory, concerned with exploring conceptions, I employ the term conceptual understanding and refer by it to an integrated and gradually refined understanding of concepts as socially constrained units of knowledge (Lakoff, 1987; Venville & Dawson, 2010) and thus oppose it in line with other science researchers (cf. Haug & Ødegaard, 2014; Schönborn & Anderson 2008a) to the memorisation of decontextualised knowledge.

In the context of the here outlined international and national historical and recent trends in science education in general and biology education in particular, which increasingly emphasise the idea of teaching core ideas and viewing science as a process, my research is highly significant. By means of mutually linking to each other the empirical collection and analysis of upper secondary students' conceptions to the educational scrutiny of the scientific theory of CMB and lesson design processes, my thesis illuminates several aspects of teaching and learning that are relevant not only for CMB education, but also the general field of modern biology education concerned with finding conducive ways to bridge between theory and practice (Hasni et al., 2016; McIntyre, 2005).

1.2 Motives

In light of the considerations that have been discussed and illuminated above, the choice of conducting this PhD-project can be differentiated first into a societal, second a research-based, and last but not least, a personal motive. In the following, I briefly summarise these motives to a comprehensible argument for the conduction of my thesis.

Societal: MLS as a discipline is perhaps more than other scientific disciplines embedded in a political context by means of its sound impact on peoples' everyday lives (Boerwinkel & Waarlo, 2011; Mc Ewen, 2021; Tibell & Rundgren, 2010). This is vividly illustrated by the health-and ethical-related questions raised in the realm of the ongoing COVID-19 pandemic. If students are to make informed decisions regarding their own and others' health, and to understand how their behaviour affects life on earth in general (McComas et al., 2018; Reiss & White, 2014; Utdanningsdirektoratet, 2021b), it is crucial that school education contributes to communicating the abstract content of modern biology in a way it is not conceived as a stable set of true facts (DeBoer, 2014; Weber, 1976); rather, students should understand core elements, idiosyncratic scientific perspectives of inquiry, and the linkage between science and society (Driver et al., 1996; Ludvigsen et al., 2015).

Lack of research-based knowledge: This motive is directly linked to the societal one and stems from the observation that MLS, in addition to the general educational challenges of biology, faces unique challenges (Tibell & Rundgren, 2010). These emanate from a constantly growing body of scientific knowledge giving rise to the problem of adequate content selection for school science education (Howitt et al., 2008; Smith et al., 2008). Furthermore, due to the abstract and interdisciplinary character of MLS, students experience sound difficulties when trying to obtain conceptual understanding (e.g., Riemeier, 2005; Verhoeff et al., 2008), which presents educators with the challenge to identify conducive teaching tools to help students overcome these. While biology education researchers have made sound efforts to meet these challenges on the level of tertiary education (Howitt et al., 2008; Michael & Modell, 2019; Rundgren et al., 2010), and in the sub-field of genetics education (e.g., Duncan & Reiser 2007), less focus has been put on exploring the scientific theory of CMB from the viewpoint of upper secondary education.

Personal interest: Linking to the above-mentioned motives, my third motive is rooted in my background: as a biologist with expertise in the fields of human biology and environmental chemistry, alongside my practical work experience as a university science teacher educator for chemistry and biology, I am motivated to better understand how to bridge the gap between disciplinary and educational content, between theory and practice (cf. Hasni et al., 2016). By analytically and empirically exploring what constitutes upper secondary students' understanding of scientific core ideas of CMB, I want to produce knowledge that not only adds to, but respectively extends existing educational theories, and has the potential to inform and improve my own and others' teaching practices, but also opens up for broader discussions such as what should be the task of biology education and the qualities of biology teachers in the 21st century (McComas et al., 2018).

1.3 Aims and research questions

With reference to the background and motives as sketched above, the overall aim of my thesis is to propose an empirical-and theoretical-based educational reconstruction of CMB for upper secondary education. Research-based knowledge about learning and teaching in science appears to be a powerful means to improve students' learning of scientific concepts in classrooms on the one hand, and to increase our theoretical knowledge about the nature of students' conceptual understanding on the other (Leach & Scott, 2002). The relevance of my thesis can thus be described as a theoretical and practical contribution to the emerging field of MLS education by means of exploring the educational challenges and opportunities of CMB as an under-researched topic. By employing the MER to a new field of science, my thesis adds useful knowledge regarding the processes of educational reconstruction as conducted within other scientific disciplines (e.g., Kersting et al. 2018; Messig & Groß, 2018; Niebert & Gropengießer, 2013). According to these considerations, my overall aim can be specified into the following research questions, which I pursued in the individual articles:

<u>1) Which scientific core ideas are essential for upper secondary CMB education?</u>

Responding to the scarcity of literature reporting on scientists' conceptions about CMB, article I aimed at scrutinising the existing scientific theory of CMB from the viewpoint of upper secondary biology education. To identify and select essential core ideas, educational textbooks dealing with cell biology on the university and upper secondary level, historical literature and recent CMB publications were analysed by employing Gropengießer's (2001, 2005) adapted version of QCA (cf. Mayring, 2010). In employing this method, core ideas were not only identified but based on scientists' language scrutinised with regard to their social and cultural grounding.

2) What are student core ideas of CMB that need to be considered for the purpose of upper secondary education?

In response to the lack of literature providing qualitative descriptions of upper secondary students' conceptions of CMB, article II empirically collected and explored these in individual interviews with Norwegian upper secondary biology students (n=9). QCA was employed to understand these with regard to content and societal and cultural grounding. The identified core ideas were subsequently compared to scientific core ideas in order to shed light on potential learning challenges and opportunities.

3) How can student and scientific core ideas be combined to develop and evaluate content and learning activities for CMB upper secondary education?

Due to the scarcity of literature taking into account students' conceptions in the process of designing and evaluating content and learning activities for upper secondary CMB education, article III linked processes of educational design to their empirical evaluation. Two teaching experiments, each with three students and one teacher (n=6), were conducted to collect students' core ideas before, during and after interacting with the learning activities in order to gain detailed insight into the nature and causes of learning difficulties that arose during teaching and thus make informed statements regarding design aspects that seem crucial for the promotion of students' conceptual understanding of CMB.

By linking background, motives and aims to the theoretical landscape and methods, this kappe document presents a synthesis of the three articles. This synthesis has been guided by the following aims specifying what I intend to practically accomplish with this thesis and what I need to theoretically understand in order to do so:

1) To understand and characterise upper secondary biology students' understanding of reconstructed scientific core ideas of CMB.
2) To construct a fruitful learning environment for upper secondary education to be tested and refined in other relevant contexts.

1.4 Outline of this thesis

In chapter I, I introduced the background, context, overall motivation and aim of this thesis. In chapter 2, I present prior research, which concerns the science education communities' efforts to bring CMB to schools. Chapter 3 looks more closely at the theoretical foundations framing the research conducted. I report on how the MER as a constructivist framework for lesson planning, combined with notions of conceptual change approaches as learning theories and experiential realism as my theory for understanding, have informed and guided this thesis. In Chapter 4 I look more closely at methodological issues, before I discuss choices for method selection and present how I proceeded to collect and analyse my data. I report furthermore on how I went about ensuring the trustworthiness and authenticity of my research, before I by the end of this chapter scrutinise the transferability of my findings and discuss ethical considerations. Chapter 5 presents the integrated findings of the three articles, which are discussed in light of the theoretical framework and prior research in chapter 6. An overall conclusion and outlook on further research round off this thesis in chapter 7.

2 Prior research

Since CMB, as sketched in the previous sections, links different disciplines (e.g., physics and chemistry) and sub-fields (e.g., genetics or cell biology) to each other, the following discussion of prior research focuses not only on studies specifically dealing with CMB from an educational viewpoint (which are scarce), but also studies looking at related topics. Since structure and function of (multi) cellular processes on a more general basis are part of lower secondary curricula across the world, while the molecular level is introduced on the upper secondary level, studies both concerning the lower and upper secondary level are included in the following. When deemed relevant, also studies on the tertiary level are included: The inclusion of studies is thereby structured along the sub-aims of this thesis; the following chapter looks first into empirical and non-empirical research concerning students' conceptions and their learning difficulties regarding CMB and other MLS concepts, reports then on the teaching and learning strategies that existing literature proposes for students to overcome their learning difficulties, and finally looks into how MLS researchers think about content selection. I want to specify in this regard that the aim of this section is not to provide a systematic review, but rather an exemplary scope of main research trends in MLS relevant with respect to the aims of this thesis.

According to empirical studies (Dreyfus & Jungwirth, 1988, 1989; Gregers & Suhr Lunde, 2021; Riemeier, 2005) and those devoting additional space to furthermore reviewing existing relevant literature on cell biology education worldwide (e.g., Flores et al., 2003; Hasni et al., 2016; Riemeier, 2005), one of the main difficulties when students learn cell biology, both on the lower and upper secondary level, seems to be understanding how individual cells relate to the overall function of organisms. This seems due to the fact that students tend to hold materialistic, anthropomorphic and teleological conceptions of cells (Kattmann, 2007a; Riemeier, 2005; Tamir & Zohar, 1991). Cells are, for example, equated with building blocks all sharing the same morphology and function (Gregers & Suhr Lunde, 2021; Riemeier, 2005), attributed with human traits like breathing or knowing what to take in and dispose of (Dreyfus & Jungwirth, 1988, 1989; Zamora & Guerra, 1993), or functions are attributed to intentional planning, such as that cell membranes surround cells in order to protect the nucleus (Riemeier, 2005). In a similar vein, students seem to attribute molecules with intentions, believing that diffusion and osmosis are directional processes aiming to establish a balance on both sides of the cell membrane (Hasni et al., 2016; Lue Leh Ping et al., 2020; Marek et al., 1994; Rundgren et al., 2010).

Upper and lower secondary students' conceptions and difficulties in understanding the functionality of cells specifically seem to be due to the fact that these are challenged when relating chemical and physical laws, such as the concept of random substance movement, energy transformation or genes as biochemical information to biological processes (Duncan & Reiser, 2007; Hasni et al., 2016; Lewis & Kattmann, 2004; Mor & Zion, 2021). It appears in this regard that learning about additional concepts on the macrolevel, for instance the structure and function of DNA, RNA and proteins, does only to a limited degree help upper secondary students to overcome their learning difficulties: Concepts like cell division and reproduction (Flores et al., 2003) and structure-function relationships across the different biological levels are still poorly understood by upper secondary students (Garvin-Doxas & Klymkowsky, 2008; Lewis & Kattmann, 2004; Marbach-ad & Stavy, 2000; Van Mil et al., 2013). It is therefore suggested that using mechanisms on the microlevel to explain macroscopic phenomena is one of the greatest educational challenges for secondary science education (Dreyfus & Jungwirth, 1990; Duncan & Reiser, 2007; Gericke & Wahlberg, 2013). Duncan and Reiser (2007) assert that this is because students are not explicitly taught how to actually use their microscopic knowledge, such as their knowledge about the molecular structure of the DNA, to explain phenomena on the cellular or higher level of biological organisation.

Science educators (Clément, 2007; Tibell & Rundgren, 2010) claim in general that teaching tools often strengthen rather than help students overcome their learning difficulties in MLS because the current system seems to emphasise rote-learning rather than conceptual understanding (Klymkowsky et al., 2003). This seems to result from the teaching tools displayed in science classrooms, such as school science textbooks, often uncritically adopting the language of scientists, that is, their domain-specific terminology or other symbolic visualisations.[4]

The challenge for education as asserted by several authors of review studies (e.g., Kattmann, 1993; McComas et al., 2018; Tibell & Rundgren, 2010) thereby seems to be that that scientific terminology often lacks obvious everyday reference or has a different meaning in everyday life. Furthermore, it is argued that visualisations often depict complex concepts in a schematised and simplified way (Clément, 2007; Cook et al., 2008; Rundgren & Tibell, 2010; Venville & Treagust, 1996). Students, who are asserted to lack the necessary experience to interpret scientific visualisations (Rundgren & Tibell, 2010; Schönborn & Anderson, 2010), seem consequently to have difficulties grasping their metaphorical meaning. In tracing the historical roots of the cell concept, Clément (2007) asserts, for example, that the persistent traditional focus on differences between cell prototypes in teaching (plant cells vs. animal cells) and their schematised depictions foster misunderstandings, such as that plant cells only have walls, but not membranes, all cells share the same morphology, and animal cells are isolated entities. To ensure that scientific terminology is actually understood by students, Kattmann (1993), scrutinising the scope of cell biology terminology, suggests therefore that it be selected with respect to its precision, clearness and consistency. For example, for educational purposes he recommends using the term *cell membrane* rather than the scientific terms *plasma membrane* or *biological membranes* because

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[4] As with the term *conceptual understanding*, also the term *visualisations* is used rather loosely in science education literature. According to the definition of language in the introductory part of this thesis, I refer to visualisations as all sorts of *external* verbal, visual and sensory symbolic expressions such as scientific symbols, chemical formulae, depictions and graphics that both shape and make explicit *internal* concepts of the mind.

it more precisely denotes the membrane of the cell. Based on their findings from empirically studying upper and tertiary students' learning processes when interacting with both animated and still images of transport processes in cell membranes, Rundgren and Tibell (2010) argue similarly that it is crucial that visualisations undergo a critical educational scrutiny in terms of what they are actually intended to depict. They claim furthermore that "no single visualisation alone can transport all the critical aspects of knowledge" (p. 244) and that animated images can be more suited as instructional tools to promote students' learning of transport processes in cell membranes and cell biological concepts in general, because they more specifically show spatial aspects and dynamic processes.

Based on empirical findings, which unfortunately are only presented to a very limited degree, C. Johnson and Luft (2001) and Venville and Treagust (1996) also argue that the problem with existing instructional tools for CMB learning is that these over-emphasise cell membranes as static. To help students overcome their difficulties, they suggest unpacking the complex fluid mosaic model in its lipid and protein parts in terms of engaging students in their own modelling processes, step-by-step emphasising the fluid and mosaic analogy of membranes. Also, other science educators have brought forth research-based arguments that engaging students in analogical modelling activities seems to be a critical strategy in MLS (e.g., Verhoeff et al., 2008) and science teaching and learning (Harrison & Treagust, 1996, 2000, 2006; Wilbers & Duit, 2002)—as a means to help students understand the hypothetical and process-based character of scientific knowledge in general, and to understand the linkage between the different levels of biological organisation specifically.

In line with these assertions, MLS educators suggest that the assessment of students' understanding should not focus on the recollection of facts but instead on such facets as analogical reasoning, the transfer and application of knowledge from one domain to another, and the mutual integration of concepts (Anderson & Schönborn, 2008; Howitt et al., 2008; Schönborn & Anderson, 20008a). In their proposal for a concept inventory for MLS on the tertiary level, Howitt et al. (2008) propose in this regard that "equilibrium" is a key concept, connecting such "big ideas" as "compartmentalization across cell membranes" and "information & communication" (p.15). According to the researchers, big ideas critical for education should address students' "misconceptions" and thus "not always [be] obvious to students" and "lie at the heart of expert understanding", as well as "connect concepts" (p. 14).

Prior research, as sketched here, provides us with knowledge regarding lower and upper secondary students' conceptions of cell (membrane) biology and the resulting learning difficulties. It is interesting that these seem often shared across different educational levels and that introducing the macromolecular level (e.g.; DNA structure) apparently contributes little to ease students' learning difficulties in upper secondary education. Furthermore, it looks like that some learning difficulties have existed for decades with educators facing challenges to find adequate strategies to overcome them. Research-based approaches to explain students' difficulties when learning cell biological concepts often regard students' lack of experiences to link to each other the distinct levels of biological organisation, and hence, to adequately interpret scientists' language. While researchers as such focus mainly on proposing different types of already existing instructional analogies, and all kinds of other visualisations as instructional tools for students to overcome their difficulties, there seems to be less effort to engage in exploring innovative design processes of these tools. In this respect I observe a tendency for MLS researchers to stay close to the mother discipline in terms of investigating how students' conceptions deviate from scientists' conceptions rather than include the first in both design of content and teaching processes. In this context, I notice furthermore that a selection of content is often discussed for advanced university level, but researchers seem to only slightly discuss or challenge the content proposed in the respective science curricula on the lower and upper secondary level in their countries (e.g., Gregers & Suhr Lunde, 2021). More specifically, there are, apart from looking at subcellular transport processes, few attempts to examine CMB from the viewpoint of upper secondary education.

Last, I observe that there seems to be a peak in the amount of research-based studies produced in the field of MLS education around 2010, perhaps when MLS first was implemented in science curricula worldwide, whereas there seems less empirical research produced in recent years. Contemporary studies reviewing existing scientific and educational literature in the field of MLS (e.g., Mc Ewen, 2021) emphasise however the need for “substantive, thoughtful, and self-critical dialogue” (Pickersgill, 2020, p. 38) between biological and educational researchers. This PhD-project aims to strengthen the existing dialogue between several discourses on the topic of CMB by means of empirically and theoretically exploring, illuminating and linking to each other different aspects of upper secondary MLS education which, as outlined in this chapter, have not been properly investigated so far.

3 Theoretical framework

In the previous chapters, I positioned cell (membrane) biology within the rapidly developing field of MLS which, according to its diverse and sound societal impacts, was presented as a key discipline in modern science. I contextualised the rapidly produced and moreover abstract content of MLS within historical and recent international and Norwegian science and biology curricula developments, demanding more student-orientated education addressing core ideas in a way that allows students to understand them. I discussed how, subsequently, a combination of societal and personal motives along with a lack of research-based knowledge featured in my interest to conduct this thesis. Emanating from these issues, I presented the overall aim of my thesis to propose an empirical-and theoretical-based educational reconstruction of CMB for upper secondary education and positioned my thesis within relevant prior research, further presenting what I argue is the gap my research wants to fill.

The chapter at hand is divided into four sections. First, I discuss how the MER as a practical constructivist theory for lesson planning framed this PhD-project. I put particular emphasis on illustrating the MER as a holistic framework rooted in German *Bildung* and *Didaktik* approaches. In the second and third section, I discuss how revised conceptual change learning theories, and experiential realism as a theory for understanding, link to the ideas of the MER. Section four sums up this chapter by means of discussing the implications for this thesis.

3.1 The Model of Educational Reconstruction as practical theory for lesson planning

By means of providing practical guidance on how to constructively solve the problem of the relation between practice and theory in biology education (Kattmann, 2007b), the MER (Duit et al., 2012; Gropengießer, 2001; Kattmann et al., 1997) has supplied the overarching framework that guided my research.

Originally developed by German biology education research communities in the mid-1990s (Kattmann et al., 1997), the MER has in recent decades gained a reputation as a holistic framework to reconstruct rather abstract science content for the purpose of instruction. As this transpired, both the disciplinary borders of biology education and the national borders of Germany were crossed. At the same time, the MER as a model for students' learning was further proposed as a practical model for teacher education and their professional development (Komorek & Kattmann, 2009; van Dijk & Kattmann, 2007). From the viewpoint of education, the multidisciplinary feasibility of the MER is shown in its application across various and rather abstract fields, for example, climate change (Niebert & Gropengießer, 2013), general relativity (Kersting, 2019), nanoscience (Laherto, 2012), plant nutrition (Messig & Groß, 2018) and moral conceptions around livestock (Tramowsky & Groß, 2015). In modern biology education, the model has been employed, amongst others, in the concepts of cell division (Riemeier & Gropengießer, 2008) and genetics (Schwanewedel, 2006). What seems to unite these projects is their aim to explore why a given science content is "worthwhile and possible to teach" (Duit et al. 2012, p. 19).

The idea, as advocated by the MER, to view existing science content not as given, but through the eyes of education, is clearly embedded in (German) Bildung and Didaktik traditions. Bildung and Didaktik are terms rather difficult to translate into English. In this thesis, I employ the common translation of Didaktik as education (McComas et al., 2018) and by that refer to a process whereby "human knowledge" is transformed into "knowledge for schooling" (Duit et al, 2012, p. 16) in order to contribute to the Bildung (literally translated as formation in English) of young people. Rather than as a product to be acquired, as implied by its traditional meaning of acquiring manners (Sjøberg, 2009), Bildung refers to a process whereby a learner develops and, in a process of self-cultivation, learns to make independent decisions. The German Bildung traditions, with such conceptions as Wagenschein’s (around 1960s) genetic learning, Klafki’s (1969) didactical analysis, and didactical reduction proposed, amongst others, by Weber (1976), were strongly embedded in Dilthey’s hermeneutical epistemology. E. Nelson (2008) asserts that Dilthey, as a neo-Kantian philosopher, strongly advocated the view that knowing is practical; it involves “bodily awareness” (p. 105) and perception. Dilthey, it seems, was a pioneer in distinguishing (natural) science as a tradition for finding objective truth in order to *explain* a given phenomenon, in contrast to the tradition of the social sciences which sought to *understand* it.

Wagenschein (1968/1999) promoted Dilthey’s view in terms of arguing that traditional (science) teaching overemphasised the memorisation and recovery of already known structures instead of teaching understanding, which involved the student in their learning processes in order to prepare them for the unknown and unusual. He argued that teaching should focus less on moving orderly upwards from the simple to the complex—by way of illustration the previously emphasised biological tradition, to a step-by-step move from single-cellular organisms to humans. Wagenschein (1968/1999) claimed that one should teach in an exemplary way by selecting examples that can represent the whole. In a similar vein, Klafki (1969) asserted that any planning of instruction had to be framed by such questions, e.g., what is the more general idea that is represented by the content of interest, while Heimann et al. (1969) put a stronger emphasis on students’ learning processes rather than the contribution to Bildung. They all argued, however, that lesson plans should be framed by addressing the potential interplay between variables such as students’ interests (why), the topic of instruction (what), the methods (how) and the materials used in instruction (by what). As a key conception of these different approaches arose the idea of *elementarisation* (German: Elementarisierung)*,* a process of identifying basic principles, general laws, *and* at the same time, reducing—not simplifying—the complexity of a given content. The obvious difficulty in this seems to find a balance between scientific correctness and accessibility for students (Duit et.al., 1997, 2012).

The here outlined examples illustrate that which were later to become key ideas of constructivist-orientated science education, as were briefly sketched out in the introduction, for instance the idea that human knowledge is a tentative and dynamic construct influenced by what a person already knows (Ogborn, 1997; Phillips, 2000), were already being implemented in the German Didaktik tradition.

The MER reflects these sketched traditions by means of emphasising that there is no true science content; rather, it has to be reconstructed for instruction in a way that ensures that students' conceptions are considered in the process of selecting content rather than taken into account as educational aspects after selection (Kattmann et al., 1997). To achieve this reconstruction, the MER proposes linking the following strands of science education research: 1) identification and analysis of elementary science content (scientific clarification) from the viewpoint of education, 2) the identification and comprehension of students' perspectives (conceptions and affective variables), and 3) the design and evaluation of learning environments with respect to the identification of students' learning processes and teaching strategies. The most critical emphasis of the MER, as visualised in figure 1, is that it regards scientific perspectives as equivalent to students' perspectives. Both are viewed as equally viable and tentative products of individual conceptions shared by a given social community (Kattmann et al., 1997).

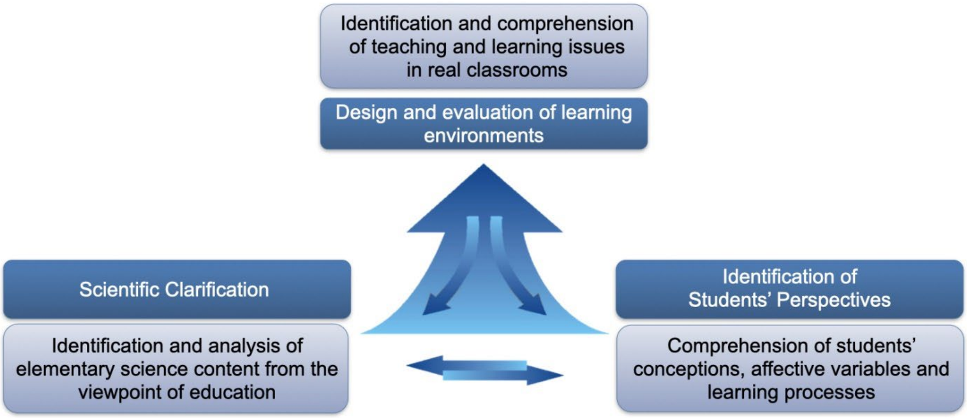

Figure 1 The process of educational reconstruction according to the MER

In its emphasis on designing content for teaching in a recursive process, the MER shares key features with other design-based research (DBR) approaches, for example, design experiments (Cobb et al., 2003), content-orientated theories (Andersson & Wallin, 2006), the concept of learning demand (Leach & Scott, 2002), or problem-based approaches (Klaassen, 1995; Knippels, 2002; Lijnse, 2004). While all these approaches wish to include students' views in the planning of instruction (McKenney & Reeves, 2012), it appears that the MER's idiosyncratic contribution lies in its idea of elementarisation (Duit et al., 2012). In line with its roots in German didactic traditions as outlined above, the MER views the scientific clarification that leads to the construction of content structure as a two-stepped process consisting of elementarisation and a subsequent *analysis of educational significance* (Kattmann et al., 1997; Méheut, 2007). This process usually draws on conceptions of hermeneutical text analysis methods of leading educational textbooks, scientific textbooks, recent publications in the field and historical literature. In particular, the consultation of historical literature is asserted to be useful in the process of scientific clarification because earlier scientists' misunderstandings are often similar to students' misunderstandings (Gropengießer & Groß, 2019; Messig, 2018). For example, as briefly illustrated in the introduction, materialistic, teleological and anthropomorphic conceptions of biological function had dictated scientists' practice for centuries, such as the instance when in 1665 Hooke became the first one to observe (dead) plant cells he called them "small boxes", because they reminded him of the rooms (cells) in monasteries (Kattmann, 1993, p. 275). In much the same way seem todays' students to think of cells as bricks with human-like features (Dreyfus & Jungwirth, 1989).

While the MER with its roots in Didaktik and constructivist movements is powerful in providing epistemological guidance for lesson planning, it does not provide information regarding the conditions for learning. This thesis therefore draws additionally on revised conceptual change approaches as a theory for learning.

3.2 Conceptual change approaches as theories for learning

The MER as a constructivist framework acts upon what Duit (1996) calls a common "constructivist core" (p. 41), namely that 1) knowledge is not passively received, but an individual construction; 2) knowledge is tentative: it is viewed as a product of learners' adaptive cognition in the course of creating viable explanations for their experiences; 3) knowledge construction is embedded in social settings, of which the learner is a part. Knowledge is, in other words, not viewed as a copy of the world outside but a viable cognitive construction of an individual in his or her attempt to make sense of the world (Taylor, 1993). This insight, which has been one of the dominant paradigms in science education research since the 1970s, has motivated some science educators' rush to identify students' conceptions of all kinds of scientific concepts. Based on notions such as Kuhn's theory of paradigm shift (1962), Piaget's notion of accommodation (1929/1974) and Posner et al.'s (1982) original theory of conceptual change, many of them believed that students' non-scientific conceptions could be replaced by the right scientific ones as long as the students experienced discontent with existing conceptions (Duit, 1996). In realm of this view, students' conceptions have been denoted with all kinds of terms, for instance "misconceptions"

(Zamora & Guerra, 1993, p. 1), “alternative conceptions” (Messig & Groß, 2018, p. 132), everyday conceptions (German: Alltagsvorstellungen) (Jung, 1986; Kattmann, 2016) or “erroneous conceptions” (Mammen, 1996, p. 188). Today, Posner’s original model of conceptual change, also called the “cold” model (Pintrich et al., 1993, p. 167), is generally viewed as outdated. This is because there seems to be convincing evidence from different disciplines and approaches that learning is not merely tied to cognitive variables but highly constrained by affective variables, namely interests, motivation, and metacognition (Kastrup & Mallow, 2016; Pintrich et al., 1993), along with the social and cultural discourses in which learners are embedded (Chi et al., 1994; Vosniadou et al., 2008). In their framework theory of conceptual change, Vosniadou et al. (2008) postulate, for example, that “initial explanations of the physical world” (p. 4) are not fragmented but build a coherent whole—a framework to be respected in education. Learning science, they argue, thus often requires more radical “ontological category shifts” (Vosniadou et al., p. 4), for example, when young children reconsider their conception of a flat earth and begin to see it as a moving astronomical object. They mean it as an evolutionary process facilitated by, for example, analogies, where children learn to understand that the earth is not as it appears to be (epistemology) and that it moves (ontology) in the sky. Venville and Treagust (1998) argue similarly that learning the concepts of genes requires an evolutionary process whereby learners develop from viewing these as particles to accepting them as biochemical processes.

Based on these findings and Strike and Posner’s (1992) revised theory of conceptual change, this thesis conceives learning not merely as a cognitive process, in the way that feeling discomfort seems a critical yet insufficient condition to foster learning processes. Rather, it seems that new conceptions are more likely to be considered when they are additionally intelligible (students understand them), plausible (they can provide explanations that exceed existing conceptions), fruitful (they can be applied in new areas), and motivating (Duit & Treagust, 2003; Venville & Treagust, 1998). To make evident the stance that I do not understand learning as a replacement of old conceptions but rather a development and recontextualisation of existing conceptions, I employ the term *conceptual development* (cf. Mintzes et al., 1991; Riemeier & Gropengießer, 2008) rather than conceptual change. Furthermore, I simply use the term *conceptions* when I speak of students' mental models. This is because I am, on the one hand, interested in examining and understanding students' conceptions about CMB regardless of their roots in classroom practice or everyday life (Paul et al., 2016). On the other hand, I want to underline that I see scientists' and students' conceptions as equally valuable starting points for learning processes rather than the latter as deviation from the first. Viewing learning as a process where learners actively develop existing conceptions in a social context means also thinking that learning cannot be directly controlled from the outside; rather, it is situated and only initiated by learning environments that consider both affective and cognitive variables (Paul et al., 2016). In the following, I discuss why I think that the planning of fruitful learning environments suggests a commitment to studying language.

3.3 Experiential realism as a theory for understanding

To fruitfully reconstruct conceptions for the purpose of lesson planning, this thesis aims not only to identify these but also understand their genesis. For this purpose, it seems expedient to draw on experiential realism. Combining insights from cognitive linguistics (Lakoff, 1987; Lakoff & M. Johnson, 1980), philosophy (e.g., Cienki, 1997; M. Johnson, 2005, 2007) and neuroscience (Kandel et al., 2013; Roth, 1996), experiential realism has in recent decades become an influential theory in science education research (Gropengießer, 2007; Gropengießer & Groß, 2019) because it explains the roots of abstract reasoning. It argues for an embodied mind that intuitively structures and processes our experiences as a basis for creating meaning (Lakoff & M. Johnson, 1980; Gropengießer, 2007). Experiences, from this viewpoint, are not conceived as memories, but dynamic interactions with the surrounding environment (Gropengießer, 2007). The philosophical notion that "structures of perceiving and doing must be appropriated to shape our acts of understanding and knowing" (M.

Johnson, 2005; p. 16) can be traced back to Kant who, according to M. Johnson (2005) and Taylor (2014), was one of the first to postulate that the mind has a critical role in shaping our perception—as opposed to empirical objectivity as asserted by positivists. Kant's view, as outlined in his opus *Critique of Pure Reason* in 1781, was that when interpretation is constrained by subjectivity, then there must be a tacit and practical, but also moral dimension to our knowledge rooted in our everyday experiences (Seung, 1989; Taylor, 2014).

While, however, Kant according to M. Johnson (2005) appeared to propose concepts as formal a priori schemas, Lakoff and M. Johnson (1980) argue for dynamic image schemas as concepts structuring an individual person's continuous bodily and social experiences such as experiences with our own body (e.g., when we eat), our orientation in space (up-down, in front and behind) or the manipulation of objects (Cienki, 1997; M. Johnson, 2005, 2007; Santibáñez Sáenz, 2002). Hence, it is argued that we as humans have our own, idiosyncratic, way of meaning-making tied to that section of the real world we fit into cognitively; something that we, literally, can make sense of and cope with in everyday life (Vollmer, 1984). As an example, due to our experiences connected with an erect body divided into a back- and frontside, it is argued that, regardless of any cultural constraints, there are universal conceptual structures that enable humans to directly understand spatial dimensions connected to such terms as *behind*, *in front of, above* or *below* (M. Johnson, 2005). Lakoff and M. Johnson (1999) argue in this context that for organisms more symmetric than us, for example, jellyfish or starfish, there is no direct meaning in such constructions like *behind* or *at the foot of the mountain*. What is thus claimed to be an idiosyncratic trait of human thought is their capability of imaginative thought;[5] a trait that appears to be present in all thought and helps us make meaning of phenomena we cannot

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[5] Even though humans seem according to their unique brain structure capable of complex (creative) imagination, it cannot be said for sure as to whether not also other animals with human-like brain structures have the ability to imagine abstract concepts. This would be an interesting field of research from both a philosophical and a biological point of view, I think.

experience directly because they are independent from the immediate input through our senses (M. Johnson, 2005). As a child, it allows one to be a princess in a phantasy world or, as an adult, we picture ourselves at the beach, when tired of working. In general, it enables us to think about possibilities, to make thought experiments as a starting point for new discoveries. This is useful in everyday life and in the realms of scientific reasoning. Einstein, for example, predicted the presence of gravitational waves long before their existence was confirmed.

From a neuronal perspective, imagination is a process that leads to a connection between two distinct domains in the brain, also called *mapping* (Kandel et al., 2013). It is this process Lakoff and M. Johnson (1980) refer to when they speak of *conceptual metaphor.* With the definition of metaphors as a process of thought, Lakoff and M. Johnson (1980) were pioneers in laying a distance to classical theories of language, where a metaphor was seen as a rare matter of poetic language. Lakoff (1993), however, understands metaphors as the opposite; as the building blocks of our every-day language, which shape our communication and the way we think and act. When we, for example, say that *we have to go our separate ways,* or that *the nucleus sits in the cell surrounded by a wall*, we imagine love in terms of journeys, and cells in terms of our experiences with containers of all sorts (cf. Riemeier, 2005).

The proposed linkage between bodily and social experiences as sources for our conceptions, where conceptions are dynamic and individual mental models and language is a tool to express and shape our conceptions, has proven to be highly useful for science education: It allows educators to gain access to students' (and scientists'!) intuitive thoughts based on the language they use, and thus shed light on the roots of often socially and culturally constrained misunderstandings (Moser, 2000; Treagust & Duit, 2008a). This in turn allows educators to more specifically consider students' conceptions in lesson design and teaching processes (Kersting et al., 2018; Riemeier & Gropengießer, 2008). For example, based on students' utterances when they learn cell division, Riemeier and Gropengießer (2008) deduced that students and scientists imagine the concept of cell division differently because they have in mind a different everyday concept of division. Students on their part seem to link division to the concept of becoming more, and consequently understand cell division as a multiplication of cells. When scientists think of division, they seem to combine several concepts and thus understand division as a process of becoming smaller *and* more. What for scientists is obvious, namely that after division there must be a process of cell growth, does not seem obvious to students. For students to understand the scientific meaning of division, that is, to link new experiences to their existing concept of division, the researchers offered the breakage of a chocolate bar as a representation of the concept of division. When subsequently talking about their observations, the students realised that division can also mean division into smaller and more pieces. I devote space to this example, because I think it vividly illustrates that, from the viewpoint of experiential realism, language is not only a crucial analytical tool for educators to uncover misunderstandings, but also a useful teaching tool to facilitate conceptual understanding. Analogies from this viewpoint, whether it be in visual or spoken form, become powerful teaching strategies because they explicitly highlight similarities between the structures of two domains (Life is like a race) in contrast to metaphors that do so implicitly (Duit, 1991; Orgill & Bodner, 2007).

3.4 Summing up

In this chapter, I argued that the MER appears powerful in providing guidance for this PhD-project because it explicitly stresses theoretical and practical dimensions of constructivist-lesson design by means of emphasising that students' conceptions must be considered in *all* processes of design (Duit et al., 1997; Kattmann et al., 1997). Rooted in German Bildung movements, the MER is specific in its emphasis that the selection of content must cast against such questions what the more general ideas of the content of interest are or how relevant they can be for students' everyday life (Klafki, 1969). This emphasis seems highly relevant regarding the social components of MLS, which I referred to in the introduction (cf. Tibell & Rundgren, 2010). I have furthermore discussed that revised conceptual change approaches (Strike & Posner, 1992; Treagust & Duit, 2008b; Vosniadou et al., 2008) inform my research by using individual conceptions as starting points to suggest concrete criteria that inform learning processes. Learning from this point of view is not only constrained by cognitive variables, but also influenced by affective variables, for instance, motivation and interests, as well as social and cultural discourses (Kastrup & Mallow, 2016; Pintrich et al., 1993). By means of linking cognition to language and bodily and social experiences, experiential realism was furthermore illustrated as a useful theory to inform my research. It proposes concrete viewpoints to embed individual conceptions within the realms of culturally shared linguistic expressions (Lakoff, 1987; Moser, 2000). It provides in this regard useful guidance for how language can be more specifically used in the process of designing and analysing the impact of teaching strategies and tools, such as analogies.

Based on the combined notions of these theories, I conclude this chapter by specifying that and how I distinguish between concepts and conceptions. I understand conceptions as a generic term for individuals' mental models (Gropengießer, 2001; Treagust & Duit, 2008 a,b), which in their most simple form can be referred to as concepts. Concepts are expressed by single words that carry a (socially constrained) meaning with them, for instance scientific terminology or everyday language (e.g., the word *cell*) (Konicek-Moran & Keeley, 2015). When related to other concepts and consequently expressed through statements, they form what is here called a notion (e.g., *cells fill bodies*) (Lewis & Kattmann, 2004). Notion, as understood here, seems to correspond to what in cognitive linguistics usually is referred to as image schemas (Gropengießer, 2005). When combined, several notions build a core idea—comparable to what Lakoff and M. Johnson (1980) call conceptual metaphor. Core ideas integrate information from multiple modalities (e.g., visual depictions such as the fluid mosaic model, or spoken and written statements). Core ideas have an explanatory character and are expressed as principles (e.g., cells are brick-like structures) and can subsequently be assembled as theories (e.g., the cell theory). Theories, as understood here, represent peoples' collected experiences of reality; their intuitive ontological assumptions about the world (Vosniadou et al., 2008) which are characterised by the fact that they must have an analytical, explanatory and prognostic function. Table 1 illustrates the presently outlined relations between experiences as concrete references, conceptions as areas of thought, and language as multifaceted tool to mutually express and influence our conceptions and experiences (cf. Gropengießer, 2001; Riemeier, 2005).

Table 1 Relationship between conceptions, experiences and language as understood in this thesis

Conceptions	**Theory**	**Core ideas (Conceptual Metaphor)**	**Notions (Image Schema)**	**Concept**
	cell theory	Cells are brick-like structures that share the same needs as humans.	Cells fill bodies. The nucleus is like the human brain.	cell body
Language		phrases, statements, models, symbols	statements, symbols, models, equations	words, terms
Social and bodily experiences	ontological experiences of reality	epistemological experiences	issues, circumstances	things, objects, people, occasions

4 Design and methods

In the following chapter I present the design of this thesis by positioning it within an ontological and epistemological landscape. I first embed my project within the scope of educational research before I further frame it within an interpretive paradigm. I furthermore discuss decisions regarding the selection of methods before I summarise how I carried out data collection and analysis in the three articles (I-III). Thereafter, I scrutinise the quality of the research conducted by means of discussing issues of trustworthiness and authenticity, and the transferability of my findings. A discussion of ethical dimensions rounds off the chapter.

4.1 Methodological approach

According to the arguments developed in the previous chapters, I position this thesis in the realm of biology education research as an individual branch within social science research rather than disciplinary research in biology. While disciplinary research tends to be restricted to identifying issues regarding subject matter knowledge (Dahncke et al., 2001), science education researchers, to a greater extent, attempt to bridge between the mother discipline and educational realms.

To better understand what biology education research is, it is necessary to point out that the biology education community, as the science education community in general, is not a homogenous group. Rather, it consists of educational researchers, science teachers, policy makers, science communicators, and scientists. According to this diversity, science education research has a variety of reference disciplines that belong to the realm of psychology, pedagogics, science and the history of science (Duit et al., 2012). By combining notions from cognitive linguistics with philosophy, educational theories, and MLS as discipline, this diversity is reflected in my thesis. In regard to the variety of disciplines that science education research refers to, it seems however necessary to position my research furthermore in terms of what are suggested as more applied and basic approaches. According to Duit et al. (2012), the attention of the former lies in placing emphasis on designing new learning and teaching practices close to the particular science domain, with a tendency to neglect students' interests, conceptions and needs. As discussed in the previous sections, it appears that much research within MLS education falls into this category (e.g., Gregers & Suhr Lunde, 2021; Lue Leh Ping et al., 2020). On the other hand, it is argued (Duit et al., 2012) that the community investigating with basic approaches mainly orients itself towards general psychological issues of learning and thereby often gives little attention to perspectives regarding science content. Some conceptual change approaches (Vosniadou et al., 2008), as well as approaches where educators investigate the cognitive skills necessary to understand concepts of MLS (Anderson & Schönborn, 2008; Rundgren & Tibell, 2010), appear to fall into this category. Regarding the aim of my thesis to reconstruct CMB for upper secondary education on the basis of scientists' and students' conceptions, I position my research in between the applied and basic approaches because I aim to contribute with both concrete practical proposals and theoretical knowledge. Such a position is supported by the philosophy of the MER as discussed in the theoretical framework, and other DBR-approaches, such as design experiments (Cobb et al., 2003).

As my thesis seeks a deeper understanding of the social construction of students' and scientists' reality, it may further be positioned within an interpretive research tradition (Lincoln & Guba, 1985; Taylor, 2014). In line with the ontological underpinning of my thesis, namely that each individual creates his or her own interpretation of an outside reality, I am more interested in shedding light on and understanding processes of learning and teaching rather than outcomes. I thus subscribe to Kant's moral philosophy and Dilthey's hermeneutical epistemology as briefly mentioned in the theoretical framework, which laid the groundwork for establishing a distinction between positivist-orientated ideas, namely the identification and explanation of axiomatic principles of nature, and interpretive traditions aimed at disclosing human meaning-making in the processes of (scientific) explanation. Since the epistemological premise for conducting research within interpretive traditions is so that knowledge is constructed in the realms of social discourses, such as a mutual cooperation between me as researcher and the participants (Creswell, 2007; Ödman, 2007), I am aware of the specific moral responsibility I have as a researcher. To do justice to this responsibility, I make transparent the potential bias emanating from my subjectivity by laying out information regarding my personal background, choice of theoretical framework and methods (Hennink et al., 2020). A more detailed discussion of my thesis' transparency is provided in section 4.5.

The interpretive stance of my thesis becomes evident in the research questions I am asking and the aims I am pursuing, as well as the flexible design and methods for data collection and analysis (Gläser-Zikuda & Hascher, 2007; Mayring, 2004). Since the design took form as my project was proceeding (Lincoln & Guba, 1985), I was at any given time allowed to understand what would work best in providing me with the data I needed. For example, the results from article I (the qualitative analysis of relevant scientific literature) informed choices regarding the methods, procedure and analysis of the subsequent collection of students' conceptions and vice versa. That is, after conducting the analysis of literature, I decided to empirically collect students' conceptions about CMB in individual interviews. For the purpose of constructing content structure for education, I found that I needed a more detailed insight into students' conceptions about CMB than existing literature provides. Employing semi-structured interviews (Kvale & Brinkmann, 2009; Niebert & Gropengießer, 2014) with individual students and teaching experiments with small groups of students (Komorek & Duit, 2004) instead of, for example, clinical interviews or classroom observation, allowed me to question in depth students' meaning making processes while at the same time following a certain structure. That means that in contrast to, for example, grounded theory (Strauss & Corbin, 1996) approaches constructing theories directly out of the data, my work was shaped by a continuous combination of inductive and deductive inquiry (Gropengießer 2005; Mayring, 2010), which is typical for processes of educational reconstruction (cf. Baalmann & Kattmann, 2001).

Table 2 below shows the design of my thesis in line with the here outlined considerations.

Table 2 Design of the thesis

Overall aim of the thesis	Educational reconstruction of CMB for upper secondary education				
Time of Data Collection	**Methods for data collection and analysis**	**Source of data**	**Type of data**	**Sub-questions pursued in the articles**	**Integration of results according to aims of this thesis**
spring and autumn 2019	QCA	selected cell membrane biology literature	text	Which scientific core ideas are essential for upper secondary CMB education?	characterisation of upper secondary biology students' understanding of reconstructed scientific core ideas of CMB.
autumn 2019	individual semi-structured interviews/ QCA	upper secondary biology students (n=9)	video	What are student core ideas of CMB that need to be considered for the purpose of upper secondary education?	
spring 2020	teaching experiments with two groups of each three students and one teacher/ QCA	upper secondary biology students (n=6)	video	How can student and scientific core ideas be combined to develop and evaluate content and learning activities for CMB upper secondary education?	construction of a fruitful learning environment for upper secondary education to be tested and refined in other relevant contexts.

The critical awareness regarding the ontological and epistemological assumptions that underpin my research is displayed, as discussed in the previous chapters, in the language I employ in this thesis. For example, I attempt to abdicate terminology traditionally used in more positivist-orientated approaches, for example, *sampling* (of participants) or speaking of the discovery of new facts. These terms connotate statistical numbers and the measuring of effect. The term sampling, for example, as used in quantitative research, implies that the sampled participants represent a larger population (Conroy & Smith, 2017; Maxwell, 2013). Furthermore, in the presentation of my findings, I employ expressions such as *my data indicate* or *my findings point to* in order to signal that my findings are subject to (my) interpretation, rather than a representation of universal truth. When I do use the term *evaluation* (regarding learning material on students' conceptions), I do not mean to suggest which learning activities work (Cobb et al., 2003) but to study how students' interactions with learning environments can inform lesson design.

In the following, I provide a more detailed discussion regarding my choice of methods before presenting how I conducted myself in collecting and analysing the data.

4.2 Choice of methods

In what follows I discuss my choice of methods as a means to scrutinise those tools that can best help me collect and analyse the data needed to achieve my aims and answer my research questions (Maxwell, 2013).

Derived from hermeneutical traditions of text interpretation, like the analysis of biblical or philosophical texts, and later Dilthey's hermeneutical circle approach (Ödman, 2007), different approaches of QCA have nowadays become a standard method in different fields of social science research, such as the study of literature or communication sciences for the analysis of all types of data sets (Goussinsky & Yassour-Borochowitz, 2012; Krüger & Riemeier, 2014). From the beginning these have mainly been quantitative. A key issue of QCA is, according to Mayring (2000, 2010), to keep the advantages of quantitative content analysis, that is, the technical handling of large data sets, and combine it with an intersubjectively verifiable interpretation of texts where a few categories represent the key features of the whole. The main difference between quantitative and qualitative approaches is hence the design: While quantitative approaches usually employ a linear and deductive design, qualitative approaches mainly use an inductive design (Hesse-Biber & Leavy, 2006). This thesis draws on Mayring's (2004, 2010) QCA approach and Gropengießer's (2005) adaptation where an inductive and deductive design is combined in a process of first formulating categories close to the material, before these are further structured into prior, theoretically derived, categories. Concerning the specific adaptation for the purpose of educational reconstruction in biology education, key features of Gropengießer's (2005) approach are its emphasis on interpreting and generalising individual students' conceptions according to different levels of complexity (here concepts, notions, core ideas and theories) on the basis of the language they use (Lakoff & M. Johnson, 1980; Schmitt, 2017; Schmitt et al., 2018). The categorisation to general core ideas and theories thereby allows for a mutual comparison between core ideas. Since this mutual and dynamic comparison between core ideas has been proven powerful in similar approaches where the purpose is educational reconstruction of abstract scientific content (e.g., Messig & Groß, 2018; Riemeier & Gropengießer, 2008) QCA according to Gropengießer (2005) and Mayring (2004), provided the overall analysis method for my thesis. It was used to identify and analyse scientists' (article I) and students' (article II & III) conceptions as collected in scientific literature, individual interviews and teaching experiments. Section 4.4 provides a detailed account of the QCA procedure as employed throughout the articles.

Interviews in all their different facets have become one of the most common methods of producing knowledge in the social sciences (Brinkmann, 2018). Since the interview is literally an *inter view*, that is, an inter-change of views between "two persons conversing about a theme of mutual interest" (Kvale, 1996, p. 14), Parker (2005) argues that completely structured interviews do not exist "because people always say things that spill beyond the structure, before the interview starts and the recorder has been turned off" (p. 53). In science education research, structured, clinical (e.g., Duncan & Reiser, 2007) and semi-structured interviews (e.g., Lewis & Kattmann, 2004) with both groups and individual students are well-established research methods.

Semi-structured individual interviews have been proven especially valuable when the aim is to study students' meaning-making processes by means of providing much space for honest, free and open-minded answers (Baalmann & Kattmann, 2001; Paul et al., 2016). Compared to the more structured variety, semi-structured interviews allow for "much more leeway for following up on whatever angles are deemed important by the interviewee", while the "interviewer has a greater say in focusing the conversation that he or she deems' important to the research project" (Brinkmann, 2014., p. 579). Hence, it is the responses of the interviewees that determine the sequence of interventions (questions, illustrations, etc.). In my thesis, I employed semi-structured individual interviews as a means of gaining an in-depth understanding of students' conceptions. The procedure for these is described in 4.3.4.

To construct and evaluate learning environments for upper secondary education, I employed teaching experiments. I used Komorek and Duit's (2004) adaptation of teaching experiments as originally proposed by Katu et al. (1993) and Steffe and D'Ambrosio (1996); these have been specifically designed to study learning processes for groups of students in the realm of education reconstruction. In their original version teaching experiments were designed to follow individual students' learning processes (Steffe & D'Ambrosio, 1996). While this version seems to suffice when "firm, pre-instructional conceptions (…) have to be further developed" (Komorek & Duit, 2004, p. 625), the adaptation for groups of students seems suitable when the aim is to combine the advantages of laboratory research, e.g., better control of variables such as noise, the handling of learning material, and documentations, with learning as a collaborative discourse with major features from real classroom situations (Komorek & Duit, 2004; Riemeier & Gropengießer, 2008). One way teaching experiments differ from interviews is that they usually, much like other design experiments (e.g., Cobb et al., 2003), follow an iterative design (thus the term *experimen*t) (Steffe & Thompson, 2000). Moreover, they are deliberately organised as learning situations (Steffe & D'Ambrosio, 1996) where the researcher takes both the role of interviewer collecting students' conceptions during, prior to and after teaching (through questionnaires) and dialogue partner, listening to students' dialogues and actively offering interventions. In this thesis, I do not employ teaching experiments iteratively, but use them similarly to Riemeier and Gropengießer (2008) and Messig and Groß (2018), namely as case studies to gain detailed insight into students' learning processes (here called *thinking pathways*). Section 4.3.5 provides a more detailed description of the preparation and procedure of the teaching experiments.

4.3 Data collection

This section devotes particular attention to discussing processes and decisions regarding the selection of literature and participants, as well as the recruitment of the latter, as these could not be discussed in detail in the articles. Furthermore, the practical arrangements, documentation, preparation and procedure of the interviews and teaching experiments are discussed in more detail here than in the articles.

4.3.1 Selection of literature

Selected chapters of the global 9th edition of *Campbell Biology* (Campbell et al., 2011) served as the main source for the identification of scientific core ideas about CMB (scientific clarification). The reasons for selecting this book were two-fold. Firstly, *Campbell Biology* is a widely used and popular standard educational textbook employed in biology courses at universities worldwide. It draws on scientists' expertise from a multiplicity of fields like evolution, cell biology, zoology and ecology. Since the majority of the authors of *Campbell Biology* also serve as "experienced and caring teacher(s)" (p. 4), the book emphasises its ambition to be scientifically correct while at the same time focusing on education. Secondly, I was already familiar with the structure and philosophy of this book from my own biology studies. According to the dynamic design of my thesis, the selection of chapters to be analysed, as well as the selection of supplementary literature, allowed me to proceed with my analytical processes. To begin with, I had intended to merely focus on chapter 7, titled

Membrane Structure and Function. However, as I proceeded with my analysis, I realised that understanding CMB from a scientific point of view requires that one understands the structure and function of cells and the organisation of multicellular organisms. Therefore, I included in my analysis parts of chapter 6, *A Tour of the Cell*, parts of chapter 40, *Basic Principles of Animal form and Function*, and parts of chapter 42, *Circulation and Gas Exchange.* Chapter 40 emphasised, among other things, homeostatic processes in animals, for instance humans, and chapter 42 highlighted exchange surfaces such as cell membranes. In line with the MER's proposal to base the identification of scientists' ideas on different types of literature (Gropengießer, 2005; Kattmann, 1997), I additionally consulted Alberts et al. (2014), which is a well-known university cell biology textbook; recent publications from the disciplinary field of CMB research (e.g., Almén et al., 2009; Watson, 2015; Yang & Hinner, 2015); educational textbooks employed in Norwegian upper secondary biology education (Grønlien et al., 2014) and original historical CMB literature (Danielli & Dawson, 1935; Gorter & Grendel, 1925; Singer & Nicolson, 1972). The selection of recent scientific publications was largely informed by the selection of newest literature in the field of biological membranes, as presented in a PhD course I was attending at the University of Copenhagen.

In line with the dynamic design of this thesis, the scientific clarification was not finished with article I. Additional scientific literature, such as Fricke (1925) or Lombard (2014), was therefore included in article II and III, respectively this kappe document.

4.3.2 Selection of school and participants

A basic premise for reconstructing science content is that it builds equally on scientists' and students' conceptions (Kattmann, 1997). To collect students' conceptions, it was therefore critical to select students who could be expected to 1) have basic conceptions regarding CMB and thus be able to articulate these in front of me/their peers and 2) be motivated by the subject of CMB (cf. Riemeier, 2005). With respect to these considerations, upper secondary biology students attending either of the two biology courses I referred to in the introduction were chosen for participation.

To establish contact with the students, I contacted the respective biology teachers of two secondary schools in Bodø via e-mail, providing them with information regarding the aim and motivation of my research, and asking that they allow me to present my project to the students and observe regular biology classroom lessons in order to better understand the social context the students are embedded in (Taylor, 2014). Since both teachers were interested in my project, I presented my project to the students at both schools and subsequently engaged in their respective classroom discourses. Presenting my study to the students entailed providing the students with spoken and written information regarding the objective and motivation of my thesis, as well as their tasks and rights of participation (see Appendix I for the information document). Practical and motivational reasons determined which school I would ultimately select: I picked the one closest to my university (as the site for data collection) and furthermore the entire class signalled a willingness to participate, having provided written consent. The final selection of students was taken by their teachers according to the criteria to select talkative students willing to share their thoughts freely and over those students merely fluent in Norwegian. This was done to ensure that the interaction between the students and me was a dialogue rather than an exam situation and to decrease the danger of misunderstandings.

In total, nine students (five girls and four boys) aged 17-18 took part in the interviews, which were carried out in September 2019, when the school year had just started; another six students aged 18-19 took part in the teaching experiments, carried out in spring 2020. Out of the six students who participated in the teaching experiments, five had already participated in the interviews. Only one girl (Lisa) had not. To pick the same students for participation in the teaching experiments was a deliberate choice because contact with the students was already established and they were familiar with the interview situation in an out-of-school setting (see the next section). The final number of students in the interviews was set during data collection, when a ”saturation” in the category system was reached, meaning no new core ideas could be identified (Gropengießer, 2005). It is critical to note here that an interview with a 10th student was not considered in the final analysis. This was due to the fact to this interview only lasted 20 minutes during which the participating students gave very brief responses without much reflection. This made it difficult for me to engage in dialogue and subsequently reconstruct his conceptions in a trustworthy way. The total number of the students participating in the teaching experiments was a practical one. The teaching experiments took place at the beginning of the outbreak of COVID-19. At that time, the teaching situation at upper secondary schools in Norway was rather unclear, as the students were not physically attending schools and teachers and students were overwhelmed with finding ways to cope with their new situation. This complicated students’ and teachers’ motivation for participation and partially explains the low number of participating students.

In September 2019, when the interviews took place, the students had, according to their teacher, had introductory lessons in cell biology. These courses addressed the basic features of cell (membrane) biology and were aimed mostly at repeating the content of the lower secondary science courses. In spring 2020, when the teaching experiments took place, the students had finished at least one of the two biology courses. I here wish to point out once more that my aim was not to evaluate their classroom lessons but to understand their conceptions and what prompted them.

4.3.3 Practical arrangements and documentation

The site for data collection was a seminar room at Nord university in Bodø. Carrying out data collection outside of school allowed for more privacy and a more relaxed and less exam-like character, while simultaneously simplifying the handling of learning materials and video-documentation arrangements (cf. Baalmann & Kattmann, 2001; von Aufschnaiter, 2014). Videography has been shown to be a powerful tool for documentation in similar studies (Messig & Groß, 2018; Riemeier & Gropengießer, 2008) because it can, compared to audio documentation, provide additional access to students' non-verbal communication, their handling of learning material, and, in the teaching experiments, a clear identification of speakers (Krüger & Riemeier, 2014). Furthermore, video has been shown to be a useful way to share research findings with others (Walker & Boyer, 2018). For documentation, I used two different types of cameras for different purposes. A GoPro camera was placed directly on the table in order to record students' handling of the learning material and record their utterances. Go-Pro cameras have previously been proven as valuable tools in documenting social interaction for research purposes as they are small and thus not very distractive. Moreover, they are convenient in their handling (Van der Kleij et al., 2019). To gain a wide-angle perspective of the interview and teaching experiment setting, I used a HX-X920 camera installed on a stable tripod at the end of the rooms where data collection took place. An illustration of the setting during the interviews and teaching experiments is provided in figures 2 and 3, respectively. The combined use of two cameras allowed me to ensure a good quality of sound and study students' meaning-making processes from different angles.

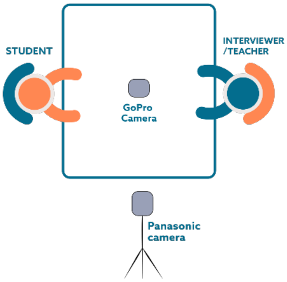

Figure 2 Setting under data collection in the individual interviews

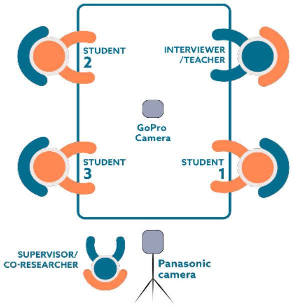

Figure 3 Setting under data collection in the teaching experiments

To create a relaxed atmosphere when conducting interviews and teaching experiments, I carefully presented the interview site to the participants, engaged with them in informal chatting, offering them something to drink, and explaining once more the objective and procedure of the data collection (Kvale & Brinkmann, 2009; Witzel, 1989). This entails that I once more assured them that my intention was not to test their knowledge but to listen to and understand their conceptions. I furthermore reminded the students of their anonymity and their right to withdraw their consent at any time and asked once more for their permission to video-record the interviews.

4.3.4 Preparation and procedure of interviews

All interviews were carried out by myself in Norwegian and lasted about 30-45 minutes without breaks. They were conducted at different points in time and days when the students could arrange to come. Students' motivation to participate might have been helped by the fact that the teacher had given the students the permission to "skip" their regular biology lessons in favour of participating in the interviews.

The final guideline used to structure the interviews (for a more detailed description of the interviews and the provision of the guideline, see article II) integrated two methodological approaches: Firstly, open- and half-open questions designed according to everyday rather than scientific terminology to collect students' conceptions regarding cell (membrane) function and structure and human physiology (as direct results from the scientific clarification), and material to facilitate students' drawing of cells and schematic depictions of the fluid mosaic model (cf. Köse, 2008; Niebert & Gropengießer, 2014; Paul et al., 2016). Secondly, I employed an "internal triangulation process" (Paul et al., 2016, p. 7) in terms of integrating similar questions on the same issue. This entailed that the students at the end of the interviews were asked to summarise their conceptions in their own words.

To test the guideline before its final use, I carried out pilot interviews with both colleagues as well as my former science teacher students. In addition to testing the plausibility of the questions asked, these interviews aimed at training my interview skills (such as how to deal with breaks in the conversation) (Kvale, 1996; Kvale & Brinkmann, 2009). It is in this regard important to note that the interview guide also underwent revision as the data collection proceeded. For example, in the initial version of the interviews the first question I asked was *Tell me, how would you explain what a cell is to somebody who has never heard about it beforehand?* This question, which was originally meant to invite the students to talk freely, turned out to rather unsettle the students because they actually had difficulty describing cells in their own words. This question was therefore replaced by the more open question *When you hear the word cells, what is it you have in mind?* which made it more evident that it was my intention to question students' conceptions rather than ask them to recollect scientific terminology. A more detailed discussion of these issues is provided in section 4.5.

While the guideline gave a certain and necessary structure to the interviews, the sequence of questions asked was guided by the dialogues I immersed myself in with the students. Excerpts of the interviews are provided in article II.

4.3.5 Preparation and procedure of teaching experiments

The two teaching experiments (group 1: Jonathan, Konrad, Hans; group 2: Lisa, Clemens and Greta) were carried out by myself in Norwegian. The experiments were designed in a way they lasted about 120 minutes including a 15 minute break. This timeframe has proven suitable in comparable laboratory studies in order to maintain but not overtax students' motivation and attention on the one hand, and to have sufficient time to introduce a coherent teaching sequence on the other (cf. Riemeier & Gropengießer, 2008). As in small student groups strong demand is put on each students' active participation, the break showed especially important in order to maintain students' motivation. During teaching, my supervisor was furthermore present as a non-participating observer. This ensured that we could share fellow experiences in the process of analysis (see figure 3 for the setting under the experiments). The students had provided consent to this.

In accordance with the method (Komorek & Duit, 2004), students' conceptions were collected individually in questionnaires prior to and after instruction and as collaborative thinking pathways (cf. Riemeier & Gropengießer, 2008). This triangulation method ensured the trustworthiness of the data but was additionally a didactical means to prepare the students on an individual basis for the subject of the teaching to come. The final design of the interventions (questionnaires and learning activities) as used in the teaching experiments are described in the method section of article III and are the subject of the discussion section of article II. The design of the interventions for the teaching sequence integrated several methodological approaches: An alternation of open questions (in the questionnaires and during teaching) using everyday language to foster students' thinking processes and their articulation during teaching; and half-open questions, interventions which aimed at combining different types of analogy-based teaching tools (e.g., schematised depictions, modelling material and three-dimensional physical models of cells) to visualise the comparison between selected concrete source domains (e.g., houses) and abstract cell membrane structure and function (cf. Tang et al., 2014; Rundgren & Tibell, 2018; Wilbers & Duit, 2002). My role alternated in this regard from that of an active dialogue partner, in much the same way as the interviews, by means of asking half-open and open questions, to that of a rather active teacher by means of offering learning activities depending on how students' conceptions developed, even directly prompting students to engage in the dialogues (Komorek & Duit, 2008; Messig & Groß, 2018). To ensure the trustworthiness of the data, it was critical that all students had equal opportunity to speak. This turned out to be especially important in the beginning of the teaching experiments. While the all boys' group more easily engaged in dialogues amongst each other, something apparently due to the fact they were equally talkative and knew each other well, the other group was initially less talkative. Specifically, Lisa was reluctant to share her thoughts, because, as she said, she did not have so many. I would therefore, in the beginning, often address her directly by, for example, asking *Lisa, what do* you *think is the task of cells?* As teaching proceeded, both groups immersed themselves increasingly in their own dialogues where Lisa’s share also increased significantly.

Since students’ responses and the progress they made during teaching determined the type of and point in time when the learning activities were offered, not all originally designed interventions were actually used during teaching; however, both groups worked with the same activities. While the inclusion of the core interventions telling the narrative of the teaching sequence (see table 2 in article III), for example, the house analogy and candy modelling activity, was determined before teaching, decisions regarding the in- or exclusion regarding some “side” activities, for example, schematised depictions of proteins or additional concept cartoons, was first made during teaching. Since, for example, the students needed more time with some interventions than originally anticipated (for example, with the candy activity), the schematised depictions of proteins were skipped. This means that I had to intuitively decide when I regarded the students open for specific learning activities. I will discuss this issue in more detail in section 4.5. To avoid students taking a passive role in terms of anticipating the different learning activities, they were not informed about the nature of the learning activities. Therefore, the learning material to be used in the learning activities was in my range, but not visible for the students. The only information the students were given was that of the teaching experiment aimed at collecting their thoughts when engaging with learning activities regarding cell membranes. I assured the students once more that there were no wrong answers and that they were expected to engage in discourse with each other.

4.4 Data analysis

4.4.1 Qualitative content analysis of selected literature

In this section the procedure of the QCA as employed throughout the three articles is outlined. In accordance with Gropengießer’s (2001, 2005) descriptions, this process consisted of three major steps, namely the processing, evaluation and structuring of the data (see illustration in table 3), which aimed at identifying general pattern (concepts, notions and core ideas) in individual conceptions in order to formulate these as comparable categories. Since the process of QCA was almost analogous in the articles, I first discuss its procedure exemplary for the analysis of the selected scientific literature (article I) before I discuss procedures of data processing for the video data from the interviews (article II) and teaching experiments (article III). I then report on idiosyncrasies in regard to the analysis of the latter.

Microsoft Word was used as the main software for the process of data analysis because it allowed me to comment on and arrange the text as I saw fit. Disadvantages of this method compared to, for example, analysis programmes such as NVivo, were that emerging categories from different data sources could not be easily compared to each other. Hence, in the course of conducting the analysis, I continuously worked on establishing a clear and, for me, functionable system that allowed me to both distinguish and align different sources of data while enabling me to share it with supervisors and co-authors.

Table 3 Stepwise procedure of qualitative content analysis as employed in the three articles

Phases	**Procedure**	**Result**
processing of the data (only for video data in article II & III)	• transcription • erasing of redundancies • transformation into individual statements of the participants	transformation of spoken utterances into written text condensation of text edited statements
evaluation of the data	• organisation of text by assembling similar statements • bundling and summarising similar statements	bundled statements condensed text
	• identification of concepts (cognitive-linguistic analysis) • explication of concepts on the basis of their experiential grounding in running text	identified concepts explicated (interpreted) concepts
structuring of the data	• assembling similar concepts to overall core ideas and theory • alignment with core ideas from other data sources	identified individual core ideas and theories regarding particular data source general core ideas across all gathered data sources

Evaluation of the data

Organisation

The analysis of the data was initialised with a perusal of the literature. The selected literature was iteratively reread, and first comments were assigned regarding recurring and apparently important statements, as well as emerging ambiguities in the authors' argumentation between different authors (Gropengießer, 2005; Mayring, 2010). Such ambiguities concerned, for example, the denotation of membranes as *plasma membranes*, *biological membranes* and *cell membranes* respectively.

In the further course of organising the text, an inductive category system was developed by means of bundling coherent text passages according to content and assigning them with subtitles, for instance *membranes allow for the formation of life.* The text passages were consequently viewed as scientists' statements and were further reduced by means of summarising the bundled statements into one general statement. A critical means of this process was to keep the sequence of scientists' argumentation, identify idiosyncratic traits of scientists' language, such as metaphors and analogies, and ensure that these were not erased in the process of text condensation (Gropengießer, 2001).

To identify metaphorical constructs, a cognitive-linguistic analysis informed by metaphor analysis as described by Moser (2000), Schmitt (2017) and Schmitt et al. (2018), along with an analysis of conceptual metaphors and image schemas as described in the literature (e.g., Cienki, 1997; M. Johnson, 2005, 2007; Lakoff, 1987; Lakoff & M. Johnson; 1980; Winston et al., 1987), was employed. This is in line with existing literature, which seeks to analyse the use of analogies and metaphors to reconstruct understanding processes (e.g., Amin et al., 2015; Kersting & Steier, 2018; Niebert & Gropengießer, 2013). To achieve this, the text was screened for all figures of speech that could be understood beyond their literal meaning as well as pre-and postpositions, for example, classes of words that are generally used to express spatial or temporal relations like *before, towards, in*, *into* and *between.* This was done to uncover the intuitive source domains scientists employ to understand CMB. *Into* and *in* indicated, for example, the CONTAINER SCHEMA[6] structuring our intuitive experiences with containers of all size and shape*,* while *between* indicated the CONTAINER-FLOW SCHEMA*,* and *towards* the PATH SCHEMA (M. Johnson, 2005, 2007; Niebert & Gropengießer, 2013). A further screening regarding verbs, nouns, body-part-metaphors or cases would subsequently lead to the enrichment of the source domains. For example, terms as *barrier* were also assembled to the CONTAINER SCHEMA along with the mentioned prepositions. The emerging metaphor was that cell membranes ARE barriers (read: cell membranes are metaphorically understood as barriers) (Lakoff & M. Johnson, 1980). While the CONTAINER SCHEMA on the one hand

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[6] A more detailed description of image schemas used in this thesis is provided especially in article I, but also II & III. In line with what is common practice in existing cognitive-linguistic literature, namely that image schemas are highlighted in capitalised letters, I adopt this notation in this thesis; also, in order to distinguish the image schemas from, for example, italicised prepositions.

indicated that scientists imagine cell membranes as rigid walls, they also use words and phrases indicating that they imagine cell membranes as dynamic (e.g., "The lateral movement of phospholipids within the membrane is rapid" (Campbell et al., 2011, p. 173). While such contradictory utterances were marked as ambiguous concerning educational purposes, the emerging metaphors were continuously revised (in this case: cell membranes are dynamic barriers).

During the whole analysis process the Anglophone online dictionary *Lexico* (Lexico.com, 2021), and the Norwegian online dictionary *heinzelnisse* (heinzelnisse.no, n.d.), especially for the analysis of the video data, provided important additional source information to understand the common everyday meaning(s) of words (Schmitt, 2017), thus shedding light on metaphorical constructs not immediately recognised as such. The consultation of dictionaries as an additional source for the analysis of metaphors has also been reported by other researchers (e.g., Riemeier & Gropengießer, 2008; Weitzel & Gropengießer, 2009). As an example, the following quotation from Campbell et al. (2011) contains several words belonging to what was identified as the same metaphor (cell membranes are barriers):

> "The plasma membrane is the edge of life, the boundary that separates the living cell from its surroundings" (p. 171).

While it seems more obvious that the "the edge of life" is meant beyond its literal meaning, the words "boundary", "surrounding" and "separates" read more normally in the context of cell biology. However, a consultation of the online dictionaries revealed, in fact, that these words can likewise be understood beyond their literal meaning.

Explication

The results from the cognitive-linguistic analysis informed the further analysis in terms of being used to explain scientists' conceptions (Gropengießer, 2001). The explication aimed, on the one hand, to further condense the bundled statements according to content into *notions* and *core ideas* and discuss the educational value of the emerging core ideas on the other. For example, even though scientists seem to view the role of membrane carbohydrates as critical for the function of cell-cell recognition, they provide more space for explaining the structure and function of membrane proteins and lipids. A primary suggestion for teaching was thus that carbohydrates might receive less attention than the other molecules. In the way the explication was conducted throughout the articles, notions were formulated as statements directly out of the running text (cf. Gropengießer, 2005; Messig, 2019), and subsequently bundled to core ideas in an iterative process of going back and forth between the explication and organisation of the text. An illustration of the process of explication is provided in Table 4 below.

Table 4 Example of explication of scientists' statements (Campbell et al., 2011)

<table>
<tr><td colspan="2">Bundled scientists' statements
"The plasma membrane is the edge of life, the boundary that separates the living cell from its surroundings. How are phospholipids and proteins arranged in the membranes of cells? In the fluid mosaic model, the membrane is a fluid structure with a "mosaic" of various proteins embedded in or attached to a double layer (bilayer) of phospholipids. Lipids and proteins are the staple ingredients of membranes, although carbohydrates are also important. The most abundant lipids in most membranes are phospholipids. The ability of phospholipids to form membranes is inherent in their molecular structure".</td></tr>
<tr><td colspan="2">Explication of statements
The authors of <i>Campbell</i> understand the structure of the PM in regard to the today widely accepted model of the membrane as a "fluid mosaic" (Notion: <i>The PM has a fluid texture</i>), apparently being unaware of the dichotomy between their concept of fluidity <i>(</i>Notion<i>:</i> <i>The PM is a bilayer of phospholipids</i>) and their concept of cell membranes as <i>barriers</i>. They imagine that different membrane proteins are "embedded in or attached to a double layer of phospholipids" (Notion: <i>Proteins are embedded as mosaic within the bilayer)</i> Also, carbohydrates are imagined as part of the membrane; nevertheless, they seem imagined as less critical for the function of membranes than proteins and lipids. Even though the term <i>fluid mosaic</i> seems obvious to scientists, it might not be for students. The term mosaic is not a frequently used term in spoken or written language; at least not in Norwegian. Although students might associate some kind of a pattern with a mosaic, it is likely that there will be no intuitive association of a mosaic, not to mention a fluid mosaic. Therefore, a graphic illustration of a fluid mosaic model of a membrane model might be promotive for learning.</td></tr>
<tr><td>Identified notions
• the PM has a fluid texture
• proteins and phospholipids make up plasma membranes
• the PM is a bilayer of phospholipids
• Proteins are arranged like a mosaic within lipid bilayer</td><td>Associated concepts
lipid
bilayer
phospholipid
Protein
fluidity</td></tr>
<tr><td>core idea (Target Domain)
chemical and physical properties allow for the biological function of cell membranes.</td><td>source domain
CONTAINER SCHEMA
CONTAINER-FLOW SCHEMA
COMPONENT/INTEGRAL-OBJECT SCHEMA</td></tr>
</table>

Structuring

In the final step of the QCA, the actual categorisation was accomplished by means of aligning the formulated individual concepts, notions and core ideas from different data sources. That means that the final core ideas as presented in the articles reflect common features shared by all scientists across the different consulted data sources. This entails that sometimes idiosyncratic concepts and notions, as formulated by only one data source, were omitted. As my research proceeded, the category system became constantly refined, particularly in line with the identification of students' conceptions.

4.4.2 Qualitative content analysis of interviews

The following section reports on the procedure of processing the video data from the interviews into text, as amongst others described by Gropengießer (2001, 2005) and Kvale and Brinkmann (2009).

Transcription

Transcribing video (or audio) data to text (written) data is a challenging process because one modality of language is transformed to another. Since the transcript is not a copy of the original data, but a first interpretation (Kvale & Brinkmann, 2009), certain judgements are required before transcription. These involve practical issues (Scott et al., 2009) like what is the purpose of the transcript, how time-consuming is its transcription, how can it be handled in an easy way and how can it remain as true as possible to the original data. I wanted a verbatim translation, i.e., no semantic cleaning of dialect or grammar, and to mark gestures, other non-verbal language (e.g., laughter) and breaks (Kvale, 1996) to assure that as much of what was really said was captured. That means students' exact phrasing was kept, so were mms, and repetitions. Bad grammar was not corrected. All non-verbal communication such as laughter was marked in brackets (laughter), short pauses were marked with three dots (…) and longer ones (more than three seconds) marked as (longer). Inaudible phrases or words were marked as ### while incomplete sentences were marked with (..).

Based on these decisions, written instructions were formulated, which functioned as guidelines for myself and a typist who carried out most of the transcriptions. The instructions were discussed with the typist before and during the transcription when the typist or I had questions (cf. Mishler, 1991). All transcripts were carefully reviewed and edited by me in terms of watching the original video data repetitive times while rechecking the transcript; in that way, sound acquaintance with the data was gained. The transcription was followed by a superficial screening of the text entailing a first comment on students' responses (for instance, students are insecure and afraid to give wrong answers), which were then aligned with comments made directly after conducting the interviews. In the course of this, all students were pseudonymised (Amalie, Bianca, Clemens, Eva, Fiona, Greta, Hans, Konrad, Jonathan and Lisa). The choice to give the students names rather than standardised labels such as student I, II and III was deliberate, as it maintained the personal relationship built up during data collection.

Editing

The editing of the text was aimed at its condensation. This first selection process entailed that all sorts of redundancies, filler words, and passages not related to the research questions (for example, the conversation taking other directions) were removed. In this process, what in reality was a dialogue between me and the student was transformed into individual statements by the student(s). This was a delicate process because it was critical to stay as close as possible to students' original statements without mistakenly erasing critical, idiosyncratic phrasings (such as metaphors and analogies) while at the same time ensuring I was not putting my words in students' mouths.

After the text was edited, it was translated from Norwegian to English. This delicate process, where the aim was to provide a translation as authentic as possible, was done in close collaboration with fellow researchers. Critical emphasis in the translation process was placed on terms that turned out to be crucial for students' understanding in the course of the cognitive-linguistic analysis and which could not be literally translated. As an example, many of the students used the spatial adverbs *utenfor* or *ute* to describe where they imagined cell membranes to be in relation to cells. In the English language, these adverbs translate literally to *outside*. However, out of the context, it seemed what students meant was that cell membranes are on the *surface* or *periphery* of cells, and not *outside* of them. The editing process is illustrated in table 5 below. The provided transcript lines show the placement in the text while the point in time refers to the original video data ensuring that the original data could be easily rechecked. In article II examples of students' edited statements, as well as direct quotes, are provided.

Table 5 Example of editing process

Transcript with line numbers	**Edited statement**	**Comment**
lines 1-16; time in the video 01.36-02,15 I (Interviewer): When you hear the word cells, what is it you have in mind? Eva: Bricks. Or in a way, bricks. I feel this is how it is explained to us in science books and so on. Like bricks which in a way build our body and other organisms. I: How do you think they look like when you say brick? Eva: I imagine there to be a bunch of cells everywhere (shows with her hands), like pretty tight. But somehow, I don't believe it is like this. The say something like this in the book, there was something, yes. I: Yes, maybe that it what one thinks of when one hears the word cell. Eva: yes, it is what I think. That it becomes a type of wall over the whole organism. I: like, for example, when you think of your own body. There are bricks in your body too? Eva: it is a little bit what I am thinking of, yes. But now I got curious. I haven't actually thought that much about it. I have thought about it as many bricks and not much more apart from that. I think we are going to learn more about it. But right now, we have gone through what is inside and transport and so on. So, we have not yet learnt the big picture. But yes, I have imagined a brick, like many bricks.	Our body is built of cells. These are like bricks which tightly lie into another in way there is a wall over the whole organism. This is how it is presented in science books at school, but I am not sure if it really is like this, because we have not yet learnt the big picture. In fact, I have not yet thought that much about it, but now I got curious.	It is interesting that Eva repeatedly expresses scepticism towards if what is written in school books actually is true. Furthermore, she seems motivated by being asked for her beliefs.

4.4.3 Qualitative content analysis of teaching experiments

Most of the procedure of the QCA for the analysis of the teaching experiments was analogous to the steps as described in the previous chapter. However, this time the aim was to sketch students' learning processes as collaborative thinking pathways, that is, describe their core ideas as they developed during teaching (e.g., Riemeier & Gropengießer, 2008; Zabel & Gropengießer, 2011). Analysing students' core ideas was achieved by means of alternating between inductive and deductive category development where the latter was according to the learning goals formulated prior to teaching (see the method section in article III), as well as findings reported in existing literature. In the process of this, students' individual responses from the questionnaires were aligned with the evolving core ideas. Treating students' individual conceptions as a collaborative discourse was justified because the analysis of students' individual responses from the questionnaires, as well as during teaching, showed that these shared similar concepts and notions (Komorek & Duit, 2004). Even though in both groups some students would argue more nuanced than others (see a more detailed discussion in section 4.3.5), and one student (Lisa) would omit questions in the pre-instructional questionnaire, the analysis showed that students' learning processes were comparable. In article III, the all boys' group's thinking pathway is described as an example for both groups' learning processes by means of providing examples from their utterances during teaching.

4.5 Quality standards

Regardless of which research traditions a researcher subscribes to, creating awareness around his or her own role in designing, collecting and analysing data (Lincoln & Guba, 1985) is crucial in order to show that the produced findings are trustable and that the research problem has theoretical and/or practical significance (Silverman, 2001).

There are different ways of approaching this awareness. In this thesis, the standards of trustworthiness, authenticity and transferability, as proposed by Guba and Lincoln (1989) and Taylor (2014) for interpretive research approaches, are discussed as alternatives to the omnipresent trinity of validity, reliability and generalisability (Angen, 2000). In line with abdicating from terminology traditionally used in more positivist-orientated approaches, this emphasises that the quality of my data does not stem from iterative rounds of data collection and controlled treatment groups, but rather “ethically sound, empowering, and beneficial relationships” (Taylor, 2014, p. 44) between me as researcher and the participants students, as well as my awareness regarding the social context that students and scientists are embedded in. Even though I think that it is rightfully asserted (Cohen et al., 2000; Maxwell, 2013) that validity and reliability can be employed in many different ways, making the discussion of their applicability for interpretive approaches somewhat ambiguous, I still think according to my theoretical framework that terminology is a powerful tool guiding our awareness in desired directions. The question that has guided my inquiry in this section is the following: “All fieldwork done by a single-field-worker invites the question, “Why should we believe it?” (Bosk, 1979, p. 193).

4.5.1 Trustworthiness and authenticity

In subscribing to interpretive research traditions, I have put stress on providing an authentic portrait of what I am actually looking at by means of giving detailed descriptions of, for example, how I went about building a trust relationship with the participating students and their teachers, and which decisions I made regarding the selection of literature and participating students (Maxwell, 2013; Taylor, 2014). During this process, decisions for conducting data collection in out-of-school settings were discussed along with issues taken to ensure students’ comfortability in a new setting (von Aufschnaiter, 2014). Furthermore, the choice of methods and documentation was justified, just as insight into the processes of data collection and analysis was provided in order to make transparent the processes of interpretation. I am in this regard confident that I addressed a common critique, namely that video documentation invades participants' privacy and influences their behaviour, also referred to as “camera effect” (Blikstad-Balas, 2017, p. 513). This confidence is, on the one hand, a result of all students reassured that they were not bothered by the presence of the cameras; on the other hand, it flows from my own comparisons between students’ behaviour in their natural school settings and their behaviour during data collection. I think here that my engagement at students’ schools and my openness towards the objectives of my project were critical criteria for building authentic relationships with the students as a means to ensure the trustworthiness of the data gained. Apart from their apparent motivation to “skip” their regular lessons, the students seemed uprightly motivated to participate, and to share their honest thoughts with me rather than providing responses they thought I wanted to hear (Taylor, 2014). The latter is asserted to be a particular threat for individual interview situations compared to group interviews (Billmann-Mahecha & Gebhard, 2014).

It has furthermore been reported how an internal triangulation and a triangulation between methods was carried out (Maxwell, 2013; Niebert & Gropengießer, 2014) in order to additionally ensure the trustworthiness of the data gained from the interviews and teaching experiments. In the teaching experiments, questionnaires and dialogues for collecting students’ conceptions before, during and after teaching were combined with the learning activities and integrated into similar questions on the same issues. In a similar vein, the interview guideline for conducting the individual interviews integrated similar questions and interventions on the same issues, as well as allowed for an alignment of the participating students’ utterances.

I have previously in this thesis anticipated that my research was clearly affected by my subjectivity (Hennink et al., 2020). Having a background as a science teacher influenced my thesis in many ways—amongst other things the way I engaged with the students and the way I planned the learning activities. For example, while I have experience in engaging with entire classrooms and small student groups, my experience in engaging in face-to-face dialogues stems mainly from oral exam situations. Much like clinical interviews (e.g., Ginsburg, 1997), these usually follow a structured set of rather closed questions aimed at probing students' knowledge. However, the aim of the individual interviews was a different one, namely to provide freedom in the questioning and students' responses in order to collect their conceptions and understand their genesis (Paul et al., 2016). Even though I think that learning the craft of interviewing (Kvale & Brinkmann, 2009) is a long and demanding process, which I only just have embarked on, I am confident that the conduction of the pilot interviews, as well as the continuous refinement of the interview guideline, ensured that I conducted the interviews in the way I intended (Niebert & Gropengießer, 2014; Witzel, 1989): Not only did I train my question technique, like alternating between open and half-open questions, and understand when it can be worthwhile to ask deepening questions, but also, I learned how to deal with breaks in the conversation (Groß & Paul, 2019; Kvale & Brinkmann, 2009). Rather than seeing the careful refinement of interview questions during data collection as a threat regarding the trustworthiness of my data, I see it as a natural and necessary issue in accordance with the flexible design of my thesis and the philosophy of semi-structured interviews (cf. Brinkmann, 2014; Groß, 2007; Niebert & Gropengießer, 2014). That also means that there is still much room for improvement regarding, for example, the design of the interview guideline. In the aftermath, I would reformulate some questions asked such as *Where in the body do you think there are cells?* because they might have contributed to strengthening students' conceptions of bodies as containers filled with cells. I think in this regard that continuously aligning my findings with those reported in the literature, and not least amongst the interviews and teaching experiments where different types of questions were being asked, ensured the trustworthiness of my data. In general, I would argue that my background as a teacher provided a strength for the conduction of my thesis.

My experience came especially useful in the planning and conduction of the teaching experiments because of their resemblance to my previous teaching experiences as outlined above. That said, I think that choosing the option where I myself conducted the teaching experiments and thus fulfilled the role of the teacher *and* researcher increased the overall trustworthiness of the data gained because no intermediary step of explaining strategy and scenario to somebody else was necessary (cf. Knippels, 2002). This advantage to have full control (in the way that is possible in flexible designs) over teaching was at the same time however also a potential disadvantage: Objectively observing and reflecting upon the teaching sequence while carrying it out myself was challenging, also with respect to that I found much of my teaching expertise to be intuitive (Polanyi, 1966; Schön, 1983): While conducting my thesis I became more and more aware that much of my knowledge as a teacher has tacit dimensions difficult to set into words (Polanyi, 1966). For example, I experienced that I had a sort of intuitive creativity that made planning and carrying out the learning activities less demanding than actually articulating my motivation for doing so (Harrison & Treagust, 2000). For example, I had previously experienced that candy can be both a motivating and useful learning material to visualise the analogy between chemical features and biological structures as long as students recognise the analogy between the learning material and the desired source domain. To model the fluid mosaic model, the choice fell therefore on *Haribo* candies, which are quite popular in Norway. Critical factors which contributed to ensuring the trustworthiness of the data gained in the teaching experiments in spite of my somewhat disabled objectivity were, as anticipated before, the sound preparation of the experiments, the presence of my supervisor during the very conduction of the teaching experiments, and our collaboration in the later hermeneutical analysis. In line with the aim of this PhD-project to propose and give insight into processes rather than outcomes, I have moreover attempted to articulate and clarify the assumptions and decisions that informed the design of learning goals and learning activities, both in the articles and this kappe document, even though I think we could, with an advantage, have been clearer about design decisions and other issues (such as both the inclusion and exclusion of teaching material) in article III. In thinking that providing transparency with regard to processes is critical to ensure that findings can be applied in other contexts (see also next section), I subscribe to other science education researchers' (e.g., Kersting 2019; Leach & Scott, 2002; Méheut, 2004) regret in what regards the absence of such descriptions in much of the published science education literature. According to the context-and situated-dependence of learning processes, I think it is not the mere description of the sequence of teaching interventions which decides on the trustworthiness and credibility of findings produced, but rather that researchers are more open about aspects of design decisions, including creativity and intuition issues, so other researchers can adapt and refine their proposals as they see fit in other contexts.

In the same way as my intuition as a science teacher featured prominently in my research, so did my intuition as a biologist. Since biological language is natural to me, I had to continuously learn to become aware of, address and reduce my blind spots (Wackerhausen, 2017). I am confident that I achieved this by being careful in selecting different types of scientific literature (with different languages and purposes), as well as employing Gropengießer's (2005) QCA as hermeneutical step-by-step method for text interpretation with particular emphasis on language. That is, by continuously scrutinising scientists' language, I became aware of my *own* scientific language and habits that I had taken for granted. I learned thus that I was more trained in thinking along positivist lines than I had anticipated. In other words, I had to learn to question scientific knowledge or at least read it more critically than I would usually have done as a biologist. Furthermore, I had to learn that thick and detailed descriptions of, for example, meaning-making processes can be as valuable as repeated rounds of data collection (Guba & Lincoln, 1989; Taylor, 2014). To learn to think more along the lines of a social science researcher within an interpretive paradigm it was very helpful to be embedded in different social discourses, such as supervisors, co-researchers, and research groups, which, unlike me, had no disciplinary expertise in MLS or biology at all. All in all, I would argue that being a biologist provided a great strength for this thesis. My biological expertise was very useful in terms of quickly orienting myself in the field of cell biology literature and conducting a credible scientific clarification in the first place.

Lastly, my study was influenced by my being German. Being a German researcher conducting research in a Norwegian educational setting, communicating research in international literature, and using a “German” framework for lesson planning, was, at times, very challenging. Provided the critical role language plays in my research, I had to continuously ensure that nothing was lost in translation. Even though I have lived in Norway for more than ten years, and am accustomed to the habits and culture, there was, for example, always a risk of mutual misunderstanding between me and the students. I could miss subtleties, as well as, for example, cultural references that were important for interpretation processes. I think that the trust relationships I had constructed with the students and the careful translation processes in collaboration with other researchers sufficiently counteracted the danger of misinterpretation (Becker, 1970; Taylor, 2014).

Being a German was, however, very helpful with regard to the fact that the bulk of MER literature is published in the German language, even though there are now trends in more international publications. That means that the English MER vocabulary is much less established than the German one, affording me the chance to come up with my own translations. For example, while the German MER literature is constant in its use and understanding of the terms *Begriff*, *Konzept*, *Denkfigur* and *Theorie* (Gropengießer, 2001) as abstractions of *Vorstellungen*, there is less consensus in Anglophone literature. In their international publications, most MER researchers seem just to employ the general terms concepts and conceptions (Messig & Groß, 2018; Paul et al., 2016)*,* while others speak of *explanation pattern* (Zabel & Gropengießer, 2011), *notions* and *principles* (Baalmann & Kattmann, 2001; Lewis & Kattmann, 2004). This was not helped by the fact that MLS researchers for their part speak of concepts as "relating to clusters of processes" (Tibell & Rundgren, 2010, p. 28), "big ideas" at the "heart of expert understanding" (Howitt et al., 2008, p. 15), "threshold concepts" (Dunn, 2019, p. 375) to change learners' view of a subject, or concept as a "general idea that has been accepted by a given community" (Konicek-Moran & Keeley, 2015, p. 5). In finally using the terms concept, notion, core idea and theory, I use a different terminology than in article III where I distinguished between terms, concepts, core ideas and theories. This is because I learned that the German Konzept has a different meaning than the English concept (Gropengießer, 2001), while I think that terms refer to the realm of language rather than thought (Gropengießer, 2001; Konicek-Moran & Keeley, 2015; Språkrådet, 2021). By choosing concepts, notions, core ideas and theories, I thus wanted to clarify that these terms belong to the realm of thought, and not language. By means of connecting to each other different concepts and notions, my definition of core ideas seems in this regard equated with the big ideas in MLS research.

In general, writing a compilation thesis, consisting of three articles during different periods of time, and together with different co-researchers embedded in different social discourses, provided great challenges. Provided the dynamic framework of the MER, the difficulty has in principle been that I could not revise the already published or submitted articles, and despite this, make the overall thesis cohere. Critical aspects I would have worked out differently are, apart from the terminology used in the three articles, some of the research questions in the articles. For example, I would add an educational aspect to the research questions asked in the first article. Even though this article has a clear focus on education, I think that it could be better reflected in the research questions, by means of, for example asking, *what is the relevance of scientists' core ideas for education?*

Rather than seeing the development of terminology in the course of conducting this thesis as a weakness, I would say it reflects the philosophy of the MER emphasising educational reconstruction as a dynamic process, and not least my own learning processes. I take in this regard as a liking to Ödman's (2007) analogy of a puzzle for analysis processes in general. I can very much identify with this picture of putting together small pieces in notorious, at times very chaotic, work to step-by-step form an increasingly clearer picture.

4.5.2 Transferability

This thesis was carried out by me as a researcher in a particular Norwegian context with participants from a particular upper secondary school selected based on their motivation to participate. As my findings are therefore highly context- and situation-dependent, they are per se not generalisable. In line with the MER's and other DBR-approaches' philosophy, my objective was not "to empirically tune what works" (Cobb et al., 2003, p. 9). However, I do have the expectation that the methods, theories and outcomes of this project can develop existing educational theories and be of practical applicability in other contexts, like that they inspire other researchers, or propose both views and concrete learning environments that teachers want to test and further develop in their classrooms or other educational settings.

It is my belief that the way I employed and combined methods to collect as well as analyse my data are essential to this expectation. Conducting Gropengießer's (2005) standardised adaptation of QCA to science education research allowed me to collect and generalise individual conceptions to elementary core ideas in a process of inductively and deductively developing a saturated category system (cf. Messig, 2018). For example, Greta, a student who participated in both the interviews and the teaching experiments, had quite sophisticated conceptions regarding the structure of cell membranes. She was the only student who referred to vesicles, deducing that cell membranes must be bendable. However, Greta too, shared most of her concepts and core ideas with the other students. Much like cell biologists share common ideas because of their similar cultural backgrounds, I think that students embedded in similar social discourses, such as, for example, the habits and culture of the Western world, share similar core ideas. This assumption comes from existing international and national literature, as referred to in chapter 2, which reports that students across the (Western) world share similar conceptions about cell biology (Flores et al., 2003; Gregers & Suhr Lunde, 2021; Riemeier, 2005). I think in this regard that Norwegian students' core ideas are just as diverse and general as other students' ideas across the globe.

The in this thesis employed version of teaching experiments (Komorek & Duit, 2004) was specifically developed to study social learning processes similar to those in real classrooms. Existing literature, which has studied the transfer of laboratory results gained from such teaching experiments to real classrooms, gives reason to believe that a "preliminary teaching and learning sequence" can be turned "into an instructional unit" (Komorek & Duit, 2004, p. 624). The teaching experiments as employed in this thesis were devoid of the iterative rounds of data collection and collaboration with teachers, as is the general idea of this approach (Steffe & Thompson, 2000) and other DBR-approaches. While such a procedure is necessary with regard to the further implementation of my results in real classrooms, as will be further outlined in the discussion chapter, the contribution of this thesis lies in its sound theoretical foundation that allows detailed descriptions and explanations of scientific and student core ideas (Taylor, 2014), which goes beyond what is yet be found in the literature (e.g., Lue Leh Ping et al., 2020; Rundgren & Tibell, 2010).

To ensure that my research is actually relevant for the (science) education community, I made continuous use of "external evaluation" (Cohen et al., 2011, p. 183) by means of presenting and receiving feedback from different national and international networks (although this was unfortunately much disabled by COVID-19) along with making use of peer-review within publication and reviewing processes. Apart from presenting and discussing my PhD-project on regular terms in the three research groups and the research school I am part of (NAFOL), I presented my research (digitally) amongst others at the European EARLI (European Association for Research on Learning and Instruction) conference, the Scandinavian NFSUN (Nordic Research Symposium on Science Education), and at German seminars and conferences such as a recent MER-seminar.[7]

4.5.3 Ethical considerations

Ethical dimensions are besides aspects of trustworthiness and authenticity critical in order to ensure the quality of well-designed and conducted research. In the previous sections I have discussed my awareness regarding my moral responsibility in making processes of planning, collecting, analysing and presenting my data as transparent as possible (Taylor, 2014). I have also kept the participating students informed about the objective of this study, their part in it, and their rights to withdraw their consent to participate at any time. The students were repetitively reminded that their utterances would be treated with utmost confidentiality and that these had no influence on their assessment at school. I have furthermore discussed my awareness of the fact that the participating students could experience that their privacy, but also their feeling of comfort, was invaded through my research (Maxwell, 2013). This concerned, for example, the presence of video cameras, the types of questions asked (Niebert & Gropengießer, 2014), and the clear distinction the students appeared, at least initially, to perceive me as a researcher as sitting on the “right” answers with them giving the “wrong” answers. I am confident in regard to the issues as discussed above, especially the authentic relationship I was able to gain with the students, that my PhD-project did not harm or disturb the participating students (Creswell, 2007; Maxwell, 2013).

Taking part in this project was entirely voluntary for all students, and they all provided informed and written consent to participate (see Appendix I for the consent form). The approval my project received through the Norwegian Centre for research data (NSD)

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[7] The digital MER seminar, which was arranged by the University of Oldenburg and took place in October 2021, invited the German-speaking MER community to share its thoughts, findings and future recommendations for research to be conducted within this framework.

ensures furthermore that the respective ethical Norwegian laws were met (see Appendix II). According to the Norwegian Ministry of Education and Research (Kunnskapsdepartementet, 2021) it is critical that researchers follow these laws in order to ensure the credibility of one's research.

To preserve the privacy of the participating students, while at the same time allowing for the sharing of my data with third parties, all their names were pseudonymised (Kvale & Brinkmann, 2009). Furthermore, other identifiers, such as the school they attended, were generalised to, e.g., Norwegian upper secondary school. All collected and analysed data are stored on an external hard disk protected with a password and only accessible to me. The participants provided consent that the video data can be shared within my research groups. To share the video data with third parties, which I might want to do in the future, issues for anonymising the participants, for instance voice and face disguising effects, will therefore be necessary.

5 Results

In the following I first briefly summarise each of the three articles before I, secondly, report on their integrated findings structured along the two overall aims of the thesis. When I in the following use the personal noun *we,* I refer to the different co-authors with whom I have been writing the articles.

5.1 Article I: Content-based and cognitive-linguistic analysis of cell membrane biology: Educational reconstruction of scientific conceptions

Article I aimed at scrutinising existing science content about CMB in order to identify and select scientific core ideas essential for upper secondary CMB education. The article was initiated because there is a lack of research-based core ideas of CMB proposed for the purpose of upper secondary education.

According to our findings, scientists hold the following educationally relevant core ideas of CMB:

- Cell membranes allow life to exist by enabling compartmentalisation.
- Chemical and physical properties allow for the biological function of cell membranes.
- Cell membranes are key factors for intercellular coordination in multicellular organisms.

These seem interrelated by what we called in the article the concept[8] of *evolution of more complex life forms*. Our results specify earlier findings regarding core ideas proposed for upper secondary and tertiary education (e.g., Hasni et al., 2016; Howitt

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[8] According to the definitions of language and conceptions as discussed and employed in this thesis, I would now speak of scientists' overall theory rather than concept.

et al., 2008; Rundgren & Tibell, 2010). According to scientists' core ideas, some sort of amphiphilic lipids came to enclose a solution of substances very different from their surroundings, giving rise to distinct compartments (amphiphilic lipids automatically assemble into bilayer structures in aqueous environments), which became the ancestor of all todays' cells and their membranes. While cells can only arise out of other cells, membranes can only arise out of existing membranes. According to scientists, membranes are therefore, together with other certain features, for example, a cytosol and DNA biochemically determining the genetic code, shared by all organisms. Hence, they must be the basic features for life. When, eventually, proteins, as products of genes, were embedded in the lipid bilayer, cell membranes, that is what became inner (enclosing organelles) *and* outer membranes in eukaryotic cells, allowed for the separation of different environments while at the same time allowing a dynamic exchange between them (von Bertalanffy, 1968; Verhoeff et al., 2008). Hence, while amphiphilic lipids determine the main structure of cell membranes, their main function is carried out by proteins, although carbohydrates are also critical for, for example, cell-cell recognition. According to their different structure membrane proteins carry out different functions: as enzymes, they maintain amongst others a certain voltage (separation of charged particles like in batteries) across membranes by means of actively controlling the exchange of charged substances, thus forming concentration gradients. The active maintenance of this potential energy is critical in order to drive biological processes (e.g., nerve transmission). As channels they allow hydrophilic (e.g., glucose) and charged substances (ions such as K+) which cannot cross the lipid bilayer to enter and leave cells. This allows for a continuous supply of substances to maintain the processes of living in the cell (oxygen continually passes the lipid bilayer). As receptor molecules proteins receive messages from other cells within the same or neighbouring organisms which they further relay to their final destination like the nucleus. This is crucial in order to guarantee that single cells are in continuous balance with their surrounding environment, that is, tissues and outer environments in multicellular organisms. In the last decades, scientists have specifically studied protein structures in relation to the functioning of membrane proteins: It is the malfunctioning or hijackings of proteins that plays a major role when the normal (multi)cellular balance (homeostasis), caused by outside agents such as corona-viruses, drugs (e.g., caffeine) or radiation, is disturbed.

We found that the fluid mosaic model as proposed by Singer and Nicolson in 1972 (figure 4) still provides the main communication tool scientists use to explain their ideas of relationships between the structure and functions of cell membranes. Historically, as well as today, the model was gradually developed and refined by means of continuously integrating and developing new hypotheses regarding, for example, the interplay and function of membrane molecules. In this way, the model integrates a multitude of concepts. According to our findings, when scientists communicate these concepts, they make use of terminology that has the potential to confuse students. This is because it often: 1) lacks obvious everyday reference (e.g., such terms as *hydrophilic*, *lipid bilayer*), 2) has a different meaning than what scientists mean to convey (e.g., *barrier, compartmentalisation*) or 3) lacks precision and clarity (e.g., the terms *plasma membrane* and *cell membranes* are used interchangeably). We argued therefore that, for the purpose of education, scientists' communicative tools need to be carefully scrutinised and translated in a way that makes sense to students.

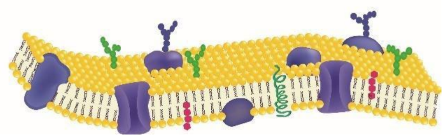

Figure 2 Schema of the fluid mosaic model as used by scientists to describe the structure of cell membranes as a mosaic of different components

5.2 Article II: Towards understanding student core ideas of cell membrane biology—An interview study to explore challenges and opportunities for upper secondary learning and teaching

Article II was concerned with empirically identifying, comprehending and explaining biology students' core ideas of CMB in order to deduce challenges and opportunities for learning and teaching at the upper secondary level. The starting point of this article was that existing literature only insufficiently identifies, characterises and explains the genesis and relevance of upper secondary students' conceptions for education.

Our findings point to interviewed students as holding the following core ideas of CMB, which must be considered for educational purposes:

- Cell membranes are static one-dimensional barriers on the surface of cells
- Cell membranes guard cells' insides and satisfy their needs.
- The structure of cell membranes is the best fit for its function.

Our data suggest that these are framed by what we in the article called the overall theory that *cell membranes exist to protect cells from the environment***.**

Our findings corroborate existing research (Gregers & Suhr Lunde, 2021; Riemeier, 2005) which reports that when students think of cell membranes they think of wall-like barriers that surround cells externally (not internally) in order to physically protect their inside, mainly the nucleus, from the outside environment. We found, interestingly, that students furthermore expressed both scepticism with regard to the apparent rigidity of cells and a curiosity to understand more about the structure and organisation of cells in their own body. Students' core ideas were deduced from the way they depicted cells (what Clément (2007) calls "fried egg model" (p. 434), see figure 5) as well as the, what we classified as, spatial, anthropomorphic and teleological statements and explanations they used when speaking of cell membranes. For example, our findings show, in line with existing research (e.g., Riemeier, 2005), that students appear to believe cell membranes to be responsible for deciding what enters and leaves cells through the holes it is equipped with. Apparently linking their own experiences with physiological processes like the uptake of food and

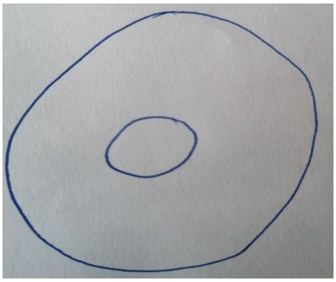

Figure 3 Schematised depiction of animal cells as depicted by students.

digestion, substances which were thought to enter were substances cells needed for their survival (e.g., oxygen and water) while harmful substances, like viruses, but also big substances, were not supposed to enter. According to their concrete experiences with food entering our body from the outside, the students appeared to think that also all substances entering cells originate from somewhere outside of the human body and serve the purpose of nutrition, rather than that they thought of different tasks and surrounding cells as providers of substances. Although the participating students seemed to think that there are many cells and water in the human body, they were unsure regarding their organisation (cf. Riemeier, 2005) to each other. According to our findings and existing literature (Hasni et al., 2016), students do not seem to properly understand the meaning scientists associate with the fluid mosaic model. Even though some of the interviewed students believed that the model does not necessarily depict reality, they seemed unaware of the models' usage for hypothesising and explaining structure-function relationships. According to our findings, only a few students were aware that the fluid mosaic model depicts proteins and lipids in the first place, and these were considered to fill cell membranes rather than contribute to their function. In line with students' ideas that substances entering cells come from outside the body, proteins were imagined to come from diet rather than being a product of genes (Duncan & Reiser, 2007; Lewis & Kattmann, 2004). According to our findings, the students believed that the bilayer structure of cell membranes is due to their function, namely to protect the inside of cells in the best possible way. Our data show that the students thought that understanding cell (membrane) biology is important in order to understand how the human body works, such as how humans get cancer; at the same time, they also thought that their everyday lives would not be affected if they did not understand it.

According to our findings, misunderstandings are likely to arrive when students learn about CMB not only because of differences between scientists' ideas on the conceptual level, but also as a result of underlying epistemological and ontological assumptions. Viewing students' core ideas from the perspective of experiential realism, we argued that when the focus is on the isolation and rigidity of cells (cell membranes as physically separating barriers), there is no need to consider cells as parts of environments such as a collaboration between cells. If, furthermore, the attention is on intentional substance discrimination and the static architecture of cell membranes, there is no need to consider and distinguish between molecular mechanisms for substance discrimination and functional outcomes nor that the architecture of cell membranes can change. If the existing architecture already is the best fit, there is little need to consider its development—either on the individual organism or the evolutionary species level. To facilitate learning CMB, we argued that students' existing core ideas offer opportunities as long as students are guided to understanding the limitations, and, at the same time as they are offered new experiences highlighting concrete aspects the students seem unaware of. To facilitate such learning processes, we proposed the following learning goals:

- to understand the *difference* between confining (isolating) and separating (organising) barriers (with regard to *all* biological membranes)
- to understand that there is a need for mechanisms to coordinate organisation.
- to understand *how* and *why* separation and coordination are achieved (reconsider the idea of static barriers and conscious gatekeepers independent of molecules).

5.3 Article III: Upper secondary students' thinking pathways in cell membrane biology—an evidence-based development and evaluation of learning activities using the Model of Educational Reconstruction

Article III was initiated because of the scarcity of research-based approaches to learning and teaching CMB at the upper secondary school level in general, and studies employing process-based designs specifically. Article III presented an educational reconstruction of CMB in a nutshell by means of linking the construction of learning activities and learning goals to key educational ideas and students' conceptions as described in the literature to their process-based evaluation. Subsequently using teaching experiments to analyse groups of students' core ideas before, during and after teaching (students' thinking pathways) allowed us to investigate the understanding that the participating students expressed concerning key educational ideas while interacting with the learning activities. A characterisation of students' learning difficulties from the perspective of experiential realism allowed us to infer critical aspects which should be considered in the further design of learning environments for CMB for the upper secondary level.

Overall, our findings indicate that the participating students understood educational core ideas of CMB when provided with learning activities designed in a way that told an intelligible, plausible and fruitful narrative as well as provided sufficient scaffolding such as interaction with peers and teachers (Treagust & Duit, 2008b; Vosniadou et al., 2008), but also time on their own. Our data indicate that the role of the teacher is critical to supporting students' conceptual development in terms of being a facilitator of peer interaction and continuously guiding students' attention to the linkage between the learning activities (Knippels & Waarlo, 2018; Komorek & Duit, 2004). Even though the role of the teacher seems critical, our data indicate that CMB learning is an active process initiated by learners themselves based on their existing conceptions. This became evident in the way the student first understood and accepted the plausibility of the offered learning activities when they could construct a linkage to previous experiences. Our data support existing views that instructional and student-generated multiple analogies (either in the form of spoken and written terminology or visual depictions and three-dimensional physical models) can be powerful tools to foster students' understanding of MLS concepts (Orgill & Bodner, 2007; Venville & Treagust, 1996) because they counteract students' lack of experience. This also confirms findings reporting that no single analogy alone can convey all the critical aspects between a concrete source and abstract target domain (Harrison & Treagust, 2006; Wilbers & Duit, 2002). Our findings furthermore indicate that students' conceptual understanding of CMB can be inferred from a recontextualization of "old" terms (e.g., proteins), respectively an increasing usage of "new" terms and the construction of analogies which refer to part-whole relationships and temporal aspects and as such are part of causal explanations. For example, did the students' usage of the terms *compartmentalisation* and *organisation* in response to the house analogy indicate that the students had reconsidered their ideas of separation as isolation in favour of the idea of separation as a means for increased organisation, (what was referred to as key educational idea 1 in table 1). Similarly, did such analogies as "natural bubbles" and "natural barriers" (see article III) as constructed by the students indicate that these had understood the plausibility of cells being spherical and dynamic compartments separated by a fatty layer from aqueous environments.

An important additional finding was that a main challenge when learning CMB was rooted in students' difficulties to link chemical features to the structure and function of cell membranes (Hasni et al, 2016; Rundgren & Tibell, 2010). Viewed from the perspective of experiential realism we deduced that this difficulty was rooted in the ontological underpinnings (Duit & Treagust, 2003; Vosniadou et al., 2008) of students' core ideas: Accepting that the inherent features of amphiphilic lipids determine the structure and function of cell membranes (candy modelling activity) certainly seemed just too far from students' idea that the structure of cell membranes is due to the purpose of function. Our findings corroborate in this regard existing research (e.g., Rundgren & Tibell, 2010) reporting that students' learning difficulties concerning the structure-function relationships of cell membranes seem additionally strengthened by their literal interpretation of schematised and simplified depictions. Since, for example, the depictions of micelles and the fluid mosaic model did neither show aqueous environments nor cell membranes as parts of cells, the students literally thought of cell membranes as one-dimensional lines. Scientific terms such *amphiphilic* and *hydrophilic* appeared subsequently meaningless to the students.

Another important result was that a critical aspect for students’ conceptual development in CMB is that they can link causal explanations of the macro-molecular level (in particular proteins) to observable physiological phenomena they can refer to from their everyday lives. This corroborates proposals and findings from molecular genetics learning (e.g., Duncan & Reiser, 2007; Gericke & Wahlberg, 2013; Knippels & Waarlo, 2018).

Adding new insights to existing findings (Hasni et al., 2016; Howitt et al., 2008; Rundgren & Tibell, 2010), our data suggest that the following aspects are critical to CMB teaching and learning at the upper secondary level:

- the difference between cells/organelles being isolated bricks vs. organised compartments
- extrapolation between spatial dimensions (one-two-and three dimensionality) to understand that cell membranes are parts of cells and that proteins and lipids are constituting parts of cell membranes
- how the presence of aqueous environments determines the spherical structure of cells and gives a meaning to cell membranes as fatty barriers between two environments
- that proteins enable the main function of cell membranes in terms of transport and communication
- that membrane proteins are produced by the cell itself according to changing environmental conditions

5.4 Integration of results—An educational reconstruction of cell membrane biology

In the following I present a synthesis of the findings presented above in the three articles according to the two-fold aim of this thesis, namely 1) to understand and characterise upper secondary biology students' understanding of reconstructed scientific core ideas of CMB and 2) to construct a fruitful learning environment for upper secondary education, to be tested and refined in other relevant contexts.

5.4.1 Characterisation of upper secondary biology students' understanding of reconstructed scientific' core ideas of CMB

Our data show in line with the MER's idea that educational reconstruction is a cyclic process linking to each other content selection (articles I & III), the identification and comprehension of students' core ideas (article II & III) and the construction (article II & III) and evaluation (article III) of learning environments. This is because the educational significance of science content becomes first evident in the comparison with students' ideas. To reconstruct abstract science content for teaching and learning, our findings corroborate existing literature (e.g., Kersting, 2019; Niebert & Gropengießer, 2013) suggesting that the combination of methods with a process-based and open design framed by experiential realism as interpretive theory can be powerful. This feasibility is due to that we were not only enabled to identify relevant scientific' and students' core ideas, respectively, but additionally shed light on their experiential genesis. This allowed us to more specifically explain the roots of their ideas, subsequently deduce potentials and challenges for learning and teaching CMB (article I & III) and design learning activities in a way that explicitly highlighted aspects of experiences we found critical for students to understand (article III).

Understanding the genesis of respective scientists' and students' conceptions was useful in terms of revealing that scientists and students often mean different things even when they employ the same language. For scientists (article I) it seems, for example obvious, that the terms *barrier*, *controlling* and *fluid mosaic* are meant in a metaphorical sense (e.g., the latter referring to the unique structure of cell membranes) in the same way such terms as *hydrophilic* and *amphiphilic* refer to chemical features of molecules. Students (article II & III) who, however, lack the experiences scientists have, interpret these terms literally and associate no—or an opposite—meaning to them. Our data show that students' difficulty in interpreting scientists' language is not only limited to scientific terminology, but also visual tools (article II & III). For example, even though the participating students assured that they were acquainted with the fluid mosaic model from earlier classroom teaching, our findings show that they were challenged to understand (article I & II) that the scientific idea of this model is to integrate a multitude of concepts in order to hypothesise *and* explain the structure-function relationships of cell membranes (article I). Viewing students' core ideas in light of the historical development of the fluid mosaic model (article I) helps to explain students' reasoning difficulties: As with scientific models in general, the fluid model was developed in a continuous process of formulating and testing new hypotheses (article I). Even though our data give reason to believe that students do not necessarily understand scientific models as concrete pictures of reality (article II), they still seem to have difficulties in understanding that models are tentative and how they can be used to deduce structure-function relationships (article II & III). Students' difficulties in understanding the scientific meaning of models appears to be related to their difficulties with themselves engaging in modelling processes (article III). Our data show in line with existing research that upper secondary students are apparently not used to thinking in the way scientists generally do, namely to first problematise and then propose step-by-step, solutions for problems (Schönborn & Anderson, 2010; van Mil et al., 2013). This extends to cell biologists more specifically, namely that they constantly explore the relationships between parts-and wholes, also called system-thinking (Knippels & Waarlo, 2018; Mor & Zion, 2021; Verhoeff et al., 2008). Our findings indicate in this regard that understanding CMB is not only constrained by conceptual challenges (such as understanding the concept of *aqueous environments*), but also epistemological (the relation between parts and wholes) and ontological (the transfer from a materialistic to a dynamic view of cell membrane structure) challenges (article II & III). This is in line with what Venville and Treagust (1996) proposed as a challenge for CMB learning, and what are suggested challenges for molecular genetics learning (e.g., Duncan & Reiser, 2007; Lewis & Kattmann, 2007).

For students who, according to our findings (article II & III), much in the same way as early scientists (article I) neither intuitively think of hierarchically organised mechanisms nor their dynamic interplay, scientific language referring to these aspects becomes meaningless unless it is translated according to students' core ideas (article III). According to the discrepancies between students' and scientists' ontological underpinnings, the greatest challenge for teaching and learning CMB at the upper secondary level seems to be for students to understand that cell membrane function relates to the existence and maintenance of critical features of *life:* While it seems more obvious for students to think of metabolism (students appear to think of cells as eating and digesting entities in terms of their experiences with human food uptake and disposal) (article I & II) as a feature of the living, it appears that the openness of living systems which allows for a continuous exchange of matter with the environment (the maintenance of homeostasis), as well as their continuous development (von Bertalanffy, 1968), seem less obvious features of the living (article I & II). In a nutshell, the learning difficulties about CMB can be specified —in part in corroboration with those as discussed for molecular genetics (Knippels & Waarlo, 2018)— as follows with regard to the integrated findings:

- domain-specific terminology and visual tools
- systems-thinking (the interference between parts and wholes including macroscopic phenomena relating to personal and social aspects)
- process-based thinking on a functional organism and functional evolutionary level

- the linkage between processes *and* systems in relation to the two-fold function of cell membranes

In the next section, I discuss how the scientific theory of CMB can in light of these considerations be turned into an educational theory for upper secondary education.

5.4.2 Construction of a fruitful learning environment for upper secondary education

The following section reports on how findings regarding the characterisation of students' understanding of scientific core ideas and students' interaction with teaching strategies and tools informs the construction of a learning environment which has the potential to promote upper secondary students' learning processes of CMB. Our findings indicate in line with existing literature (Hasni et al., 2016) that students are confused by the scientific idea of the processes of diffusion and osmosis (article I & II). This appears to result from understanding these processes as linking to respective different ontologies, that is, understanding how the principles of innate matter (physics) link to processes (biology) and mechanisms (biology and chemistry). Since students, according to our findings, at least partially link chemical principles, like solubility and randomness, but not physical principles, such as energy transduction and electrochemistry, to cell membrane structure and function, it seems necessary to first establish an understanding of the marriage between chemistry and biology before additionally emphasising physics in upper secondary education. This is in line with the historical development of scientific CMB theory (Lombard, 2014), but seems to somewhat contrast existing educational proposals made for CMB learning and teaching on the upper secondary level (e.g., Rundgren & Tibell, 2010). Our findings corroborate the reported usefulness (C. Johnson & Luft, 2001; Rundgren & Tibell, 2010; Venville & Treagust, 1996) of multiple analogies as a strategy for learning CMB because they counteract students' lack of experience (article III). It therefore appears from our findings that not only the combination of analogy-based tools, but also the different modalities of these (speech, vision, and it can seem also touch) and spatial physical dimensions, are beneficial for students' learning processes (Prain & Waldrip, 2006; Rundgren & Tibell, 2010; Tang et al., 2014). In line with this, our findings indicate that an inquiry-based strategy based on students' own language rather than scientific terminology can be a useful strategy to engage students in small groups to talk, pose questions and debate them rather than come up with answers (Riemeier & Gropengießer, 2008; Verhoeff et al., 2008). Constructing their own language (such as physical models or spoken analogies) of CMB (article II & III) seems a useful counterbalance to adopting scientists' language even when students' language lacks scientific correctness. This extrapolates existing research, for example, proposing that student-generated models (C. Johnson & Luft, 2001; Verhoeff et al., 2008) and instructional analogies that make explicit students' conceptions (e.g., Riemeier & Gropengießer, 2008) are powerful tools for upper secondary MLS education.

Offering analogies as a general remedy for CMB learning seems, however, in light of our findings (article II), insufficient. It seems critical (article III) to construct these as clear, precise and unambiguous as possible in a way that does not convey too much information all at once (Rundgren & Tibell, 2010). It seems in this regard necessary to carefully scrutinise what kind of information educational analogies are supposed to convey: If, for example, the aim is to convey the dynamic aspect of cell membranes, then the house analogy is flawed. If, however, the aim is to guide students' attention to the aspect of cellular organisation and the functional analogies between cells, this analogy seems powerful. Our data (article III) suggest that students have difficulties interpreting schematised depictions (e.g., fluid mosaic model) beyond their literal meaning, if they lack a clear rationale for how to interpret them (cf. Schönborn & Anderson, 2008b). It seems critical for students' learning processes of CMB that they are provided with sufficient time to become acquainted with the learning material, especially when it is unfamiliar. Even though we did not ask the students if they had ever used candy as a learning material before (article III), it appeared from the way the students engaged with it that they had not. Much like Knippels and Waarlo (2018, para. 8) emphasise the need to frame genetics learning with “local” and “global” motives, our data (article II and III) indicate that addressing individual as well as social aspects of knowledge (Driver et al., 1996; Méheut, 2004) seem further critical aspects of not only rendering CMB intelligible and plausible, but additionally fruitful to the students, in a way that they can employ in their everyday lives (article III) (Duit & Treagust, 2003). Our data point to (article III) learning goals as principles to guide the design of learning environments for CMB learning and suggest that teaching should make explicit what we found to characterise students’ understanding processes (the gradual transfer to mechanistic and process-based explanations and descriptions) (article III). In line with addressing students’ individual knowledge, our data indicate that it is crucial that students are not only provided with sufficient scaffolding for collaborative discourse, but also individual thinking processes (e.g., as with the questionnaires and the concept cartoons) (article III) (Bennett et al., 2010).

According to the here outlined considerations, I propose a refined and more holistic learning environment for CMB upper secondary learning and teaching to be tested in other relevant educational contexts like real classrooms (see table 6). The proposed learning environment links the empirical findings of my research with existing ideas on teaching and learning MLS concepts as emphasised here (e.g., Knippels & Waarlo, 2018; Riemeier & Gropengießer, 2008; Schönborn & Anderson, 2010; Verhoeff et al., 2008) with concrete ideas from the German didactic traditions on which the MER is based and which have been found useful while conducting my research, namely Klafki’s (1969) and Heimann et al.’s (1969) models of lesson planning. In a nutshell, the proposed content structure (in the sense of a coherent teaching unit) emphasises the interplay between the elementary ideas for students to understand CMB (*what*), learning goals as clear statements of what learners should be able to know and *do* during and after instruction (including interests and values), teaching strategies that specify on a meta-level *how* students can understand the core ideas, and concrete teaching tools (*by what*) to foster learning.

Table 6 Empirical-and theory-based proposal of a learning environment for upper secondary CMB teaching and learning to be tested and revised in other contexts

What **Content Structure**	**Why and What students should understand** **Learning goals**	**How** **Teaching strategies (How teachers can promote students' understanding)**	**By what** **(Key design aspects for) teaching tools**
introduction	discuss how and why membranes came into being and why they are crucial for the formation of cells (life)	encourage inquiry-based cooperative learning environments by changing between small group- and individual activities explain to students the rationale and aim of the teaching sequence such as that they are expected to use their own language instead of scientific terminology, to pose questions and discuss with each other; give students sufficient time to think on their own	interventions that invite discussion, such as spoken or written open (controversial) statements and questions (why-and how) as, for example, in concept cartoons
the concept of compartmentalisation across species and cell types (organisms as independent and **enclosed** entities)	discern between single, isolated compartments and several collaborative compartments with regard to functional outcomes (**organisation**)	employ an inquiry-based strategy to offer m multiple instructional analogies which make explicit and challenge students' conceptions; make sure to iteratively return to analogies during teaching and ask students about the main message of these change between tying in on and confronting students' conceptions with their own phraseology ask students to draw single cells and cells in a collaborative network and to present a rationale explaining their drawings	**analogy-based** tools which students are familiar with and which visualise the linkage between concrete source (e.g., houses) and abstract target (cells/organisms) with regard to part-whole relationships student-generated drawings of cells
	explain the difference between pro-and eukaryotic cells and think about why the latter gave rise to multicellular organisms		
	recognise the need for compartments to be connected to each other and to exchange information if they are to contribute to the overall organisation of the whole		
the concept of the lipid bilayer as **fatty** barrier between aqueous environments (**conserved** cell membrane structure)	recognise that there is a difference between human intentional decision-making and molecular mechanisms in regard to substance passage at cell membranes	ask the students what they think is the role of scientific models and if they think that models can have pitfalls make students' conceptions explicit by asking them to discuss and test their ideas regarding cell membrane structure ask the students to deduce cell membrane structure which considers the chemical structure of membrane lipids	step-by-step visualisation of structure of membrane lipids and proteins (two-and three-dimensional models) three-dimensional physical and/or dynamic visualisations of how aqueous environments affect the behaviour of substances, and as such the structure and function of the lipid bilayer (e.g., fat droplets in water)
	explain how chemical features of membrane lipids explain barrier function of membranes (lipid bilayer) regardless cell/organism type		
	discern amphiphilic lipids from hydrophobic lipids and other hydrophilic and hydrophobic substances		
	explain the use of (amphiphilic) lipids in daily life and discuss their constant renewal in the membrane		
	explain how the lipid bilayer determines which substance can (not) pass by discussing the concept of permeability		
	contextualise the lipid bilayer within the fluid mosaic model on a one- two-and three-dimensional level		

(organisms as **open** and **dynamic** systems with **idiosyncratic** cell membrane structure) the concept of **different proteins** to facilitate the maintenance of **balance** as 1)facilitators for (active) exchange of substances impeded to cross the lipid bilayer	explain how proteins might "solve" the problem that large, and hydrophilic cannot pass the lipid bilayer and deduce the structure of transmembrane proteins (hydrophilic surface and hydrophilic centre)	ask the students open questions which foster dialogues about the function and origin of membrane proteins make students' conceptions explicit by asking if all cells have cell membranes and what is the difference between these and cell walls and from cell type to cell type and species to species	multiple analogies making explicit the different functions of proteins; e.g., the lock-and key analogy to emphasise that proteins differ in their structure and function
	recognise that membrane proteins determine most of the function of cell membranes		
	recognise that proteins are both the product of our diet and our genes		
	describe the basic structure of proteins and contextualise proteins within the fluid mosaic model on a one- two-and three-dimensional level (be able to model an own fluid mosaic)		
2) facilitators for intercellular communication	recognise that cell types and organisms differ in membrane protein composition	make students' conceptions explicit by asking what happened if cells had no mechanisms to protein composition of cell membranes	everyday examples of physiological phenomena students are familiar with (e.g., nicotine or caffeine consumption)
	discuss why cell types differ in protein composition and what can be potential tasks of proteins		
	recognise that cells can produce new membrane proteins or reduce their density in regard to external stimuli and explain how this affects the maintenance of homeostasis		
	explain how the function of membrane proteins is linked to observable physiological phenomena		
conclusion	discuss other examples of how mechanisms of the molecular level bring about effects on the organism level	ask the students to come up with own everyday examples ask the students if, how and why they have revised their conceptions about cell membranes and the nature of scientific knowledge	open questions for students to individually think about (e.g., by writing) their own learning processes and come up with own questions
	explain how the different concepts link to each other		
	discuss how understanding of molecular mechanisms of cell membrane function can affect your decisions regarding yours' and others' health and how understanding that biological structures are conserved affects your understanding of humans amongst other species		

6 Discussion

Scientific knowledge produced in MLS has an increasing impact on peoples' daily lives by means of offering technological advances and influencing reasoned decisions about a persons' health. At the same time, it is not very accessible to students and the general public. To select and transform core ideas of MLS in a way that ensures they are understood by school students and become applicable for different aspects of their everyday life is therefore a major educational concern across the world (cf. Bayerisches Staatsministerium für Unterricht und Kultus, 2004; Boerwinkel & Waarlo, 2011; McEwen 2021), and in Norway (Gregers & Suhr Lunde, 2021; Utdanningsdirektoratet, 2021b). This thesis addresses this concern by means of venturing into a process-based exploration of CMB as an important scientific theory and yet under-researched topic from the viewpoint of upper secondary education. The findings of my PhD-project are presented in three articles with the attempt to answer the following research questions:

- Which scientific core ideas are essential for upper secondary CMB education?
- What are student core ideas of CMB that need to be considered for the purpose of upper secondary education?
- How can student and scientific core ideas be combined to develop and evaluate content and learning activities for CMB upper secondary education?

Based on the overall aim of this thesis, namely to propose an empirical- and theory-based educational reconstruction of CMB for upper secondary education, this discussion chapter scrutinises the individual findings of the articles. Furthermore, a synthesis of the findings is provided according to previously presented background, theoretical framework and prior research.

Reflecting the ideas of the PhD programme the study of professional praxis which I am attending, my approach to pursuing this thesis' aims has been an interdisciplinary one: It has been concerned with generating innovative theoretical and practical knowledge relevant to the international, and Norwegian, field of modern biology education. In line with this, methodological considerations regarding my approach round off this discussion chapter. A final chapter provides an overall conclusion of my thesis along with implications for theory and practice and recommendations for future research.

6.1 Approaching an educational reconstruction of CMB for upper secondary education

In line with the MER's philosophy as presented throughout this thesis, three components that featured prominently in my approach of an educational reconstruction of CMB could be specified. The following discussion is structured around these components and their linkage to each other; namely the critical analysis and selection of relevant scientific core ideas, the identification, analysis and explanation of student conceptions and their learning processes, and the design and evaluation of teaching and learning strategies.

6.1.1 Critical analysis and selection of relevant scientific core ideas

Since major curriculum developments started to take form in the realm of the increasing influence of constructivist perspectives in the 1960s (DeBoer, 2014; Sjøberg, 2009), science educators have been concerned with selecting scientific core ideas: These core ideas should be both anchored in students' minds and at the same time represent the nature and processes of a scientific discipline rather than presenting it as an unquestioned body of accumulated facts (Wagenschein, 1968/1999; Driver, 1989). My thesis offers a research-based proposal for how such a selection can be approached. It thus makes an important contribution to the emerging field of MLS education which, in light of the rapidly growing body of abstract and interdisciplinary scientific knowledge (Howitt et al., 2008; Tibell & Rundgren, 2010), is particularly concerned with the selection of adequate content. By means of employing the MER as practical framework for lesson planning having its roots in German Bildung movements, my thesis provides analytical evidence that its notion of elementarisation followed by an analysis of educational significance is highly relevant to the clarification of science content in the realms of the above-described constructivist-orientated curricula innovations. Following this notion, my approach to content selection was not guided by a reduction and simplification of existing content so upper secondary students may understand it; rather, from the outset it involved a critical scrutiny of CMB literature in order to identify essential core ideas worth teaching (Duit et al., 1997, 2012; Klafki, 1969). The outcomes of this thesis show that such a scrutiny also entails looking at scientists' view of the nature of their particular discipline (cf. Kattmann et al., 1997)—such as the various processes leading to the generation of the fluid mosaic model of cell membrane structure which after its first proposal in 1972, still is the best possible, continuously refined, and hypothetical explanation scientists have about molecular processes in cell membranes (Nicolson, 2014).

In corroboration of existing research from different fields of science (e.g., Kersting et al., 2018; Tramowsky & Groß, 2015), my research shows the usefulness of combining the MER with experiential realism in order to not only identify, but also interpret, science literature according to underlying scientists' conceptions and their contextualisation within socially and culturally constrained concepts (Lakoff & M. Johnson, 1980; Moser, 2000) idiosyncratic for the particular scientific community (Leach & Scott, 2002). Such an approach supports, as I see it, the view (e.g., Treagust & Duit, 2008a) that there is compatibility between sociocultural (advocating the social distribution of knowledge) teaching and learning theories and conceptual change approaches (advocating the viability of individual mental models) (e.g., Lave & Wenger, 1991) in science education: both create awareness of the contingency of scientific knowledge by means of emphasising language as the lens through which people communicate and experience reality. As already stated by Einstein and Infeld

(1938): “Physical concepts are free creations of the human mind, and are not, however it may seem, uniquely determined by the external world” (p. 31). In line with this contingency, this thesis shows that scientists’ conceptions about CMB are more ambiguous than they seem at first sight and that this ambiguity is critical to consider for educational purposes: while it might not interfere with scientists’ understanding it can be counterintuitive for students. According to the findings of this thesis, this ambiguity is amongst others the combined result of scientists’ tendency to keep terminology and other modes of language (e.g., depictions and models) as remnants from the past and use it along with modern terminology; terms such as *plasma membrane*, *plasmalemma*, and *cell membrane* or the term *cell* itself (Kattmann, 1993; Lombard, 2014). They furthermore seem to link to each other a variety of concrete, in everyday life rather distinct experiential source domains (like movement and containment) (cf. Niebert et al., 2012; Riemeier & Gropengießer, 2008), and thus give a meaning to terms or models different from what seems usual in an everyday life context (for example, the terms *compartmentalisation* or *barrier* and their respective depiction in the fluid mosaic model).

The point I want to make here is that for the purpose of constructivist-orientated education, it is equally crucial to critically inquire into the relevance and adequateness of both students’ and scientists’ language (Baalmann & Kattmann, 2001) in order to understand the roots of their conceptions and thus select essential core ideas for teaching accordingly. Thus, I argue that it falls short to simply adopt the viewpoints of scientists when considering the purposes of education: for example, when Rundgren and Tibell (2010) present as an “intended object for learning” that “the cell membrane consists of a bilayer composed of lipids of which phospholipids are the most abundant” (p.235) and reduce the content of CMB to transport processes only. Further, it is counterintuitive to make teaching more “effective” by means of remediating students‘“misconceptions” with the “correct scientific ideas” (Howitt et al., 2008, p. 14). The argument made here is that scientific correctness should be replaced with an educational applicability as an interplay of the reconstructed and selected elementary scientific core ideas as the aims of education and identified and selected student core ideas as opportunities to get there. Selection processes, as found in this thesis, regard in this context both students' and scientists' ideas so that a mutual aim, adequate from both viewpoints, can be reached.

Modern (!) scientists' tendency to give everyday terms a different meaning is, according to the findings of this thesis and prior research (Morange, 2008; Verhoeff et al., 2008), rooted in their "explanatory context" (Van Mil et al., 2016, p. 518): They are able to observe the dynamic interplay of macromolecules in a multicellular context; a possibility neither early scientists nor todays' students had and have. In other words, scientists seem to have a "conceptual understanding that overrides the incorrect terminology" (Konicek-Moran & Keeley, 2015, p. 6). While students, and people in general, seem to have gathered sufficient experience to, for example, overrun the literal meaning of the sunset as an "illusion of the apparent motion of the sun in the sky" (Konicek-Moran & Keeley, 2015, p. 6), they appear to lack sufficient experience with multicellular behaviour. Hence, they have difficulties to override the incorrect terminology and visual modes of language, namely that cell membranes are rigid barriers with molecules *inside* of them rather than that the latter are their constituting *and* dynamic components. In lack of this experience, it seems, as will be discussed in the next section, it is necessary that students, in the same line as early scientists, first become convinced by the thought that cell membranes exist in the first place—and are not just interchangeable with cell walls. Corroborating findings from Baalmann and Kattmann (2001) empirically exploring students' learning of (molecular) genetics, while at the same time contrasting outcomes from other studies (Hasni et al., 2016; Howitt et al., 2008; Rundgren & Tibell, 2010), my findings indicate that, in order to be meaningful for students, science content of CMB needs to be contextualised within proximate functional how-questions (as the level of cell types and organisms) and ultimate functional why-questions (the level of continuously evolving species) (Mayr, 1961/2004). This seems necessary in order to emphasise reasons for diversity (proteins as main actors to carry out *varying* functions in order to ensure the maintenance of homeostasis in both single-and more complex multicellular organisms) along with the general principles of CMB structure-function relationships conserved in *all* organisms (the lipid bilayers' inherent ability to compartmentalise thus separating a different inside from organisms from its outside). In emphasising the two-fold functionality of CMB, namely its ability to enclose spaces and at the same time facilitate their mutual openness, I come to think that Morange's anxiety for the "death of molecular biology" seems justified (2008, p. 31); at least for educational purposes. In adding macromolecules to the existing levels of biological organisation, it can appear that the original motive driving biologists, namely to study living phenomena as distinct from inanimate matter, became somewhat obscured by the sudden run on exploring mechanisms as a means to explain the functions these carried out in organisms. For the purpose of education, it seems that in light of the findings of this thesis it is necessary to emphasise that exploring and understanding CMB is above all motivated by biological questions, supplemented by the "pure" sciences chemistry and physics, and applied sciences such as medicine.

6.1.2 Identification, analysis and explanation of student conceptions and learning processes

From studying students' learning processes and their conceptual understanding, it is possible to gain in-depth insight into learning difficulties and hence determine how different designs impact students' learning, motivation and cooperative discourse in teaching situations (cf. Méheut, 2004; Riemeier & Gropengießer, 2008; von Aufschnaiter, 2014). In the following I scrutinise my approach of exploring students' conceptions about CMB together with discussing how the findings provided here can be of practical and theoretical use for the CMB community specifically and the MLS community in general, which occupies itself with finding ways to counteract students' persistent rote-learning strategies (cf. Tibell & Rundgren, 2010).

In accordance with existing research (Paul et al., 2016; Pintrich et al., 1993; Riemeier & Gropengießer, 2008), my findings suggest that providing student-orientated education means to reconstruct and understand what are the most relevant student conceptions to be respected during teaching and how this knowledge affects further choices concerning lesson design such as teaching strategy and tools (Baalmann & Kattmann, 2001; Duit et al., 2004). As has been anticipated in the previous section, reconstructing students' conceptions not only means being aware of their unfolding on the conceptual level, but also how they are organised epistemologically and ontologically. Only if students' conceptions are contextualised in this way within a broader social context will the congruences and differences between the meaning students and scientists associate with critical concepts (e.g., the lipid bilayer) become evident (Duit & Treagust, 2003; Gropengießer, 2007). For instance, the findings of this thesis reveal that even though students have in mind cells as spatial entities and cell membranes as their gatekeeping barrier, this imagination differs epistemologically and ontologically from scientists' concepts of compartmentalisation and multicellular coordination as biochemical processes respectively. As found in this thesis and in line with what earlier research reports about students' conceptions of cells in general (cf. Riemeier, 2005), students tend to attribute cell membranes with human characteristics (anthropomorphic explanations) and to explain their structure teleologically: for example, in terms of the purpose of protection rather than by the mechanistic causes by which cell membrane functions arise. Interpreting these conceptions according to students' (lack of) experiential grounding, their conceptions become understandable: When cell membranes are understood as means to isolate cells and protect their insides, there is little need for students to consider cell membranes as critical structures for the maintenance of living processes which continuously exchange matter with outside environments (cf. Butenand, 1955). The significance of this insight is that it, more specifically than existing literature (e.g., C. Johnson & Luft, 2001; Gregers & Suhr Lunde, 2021), pinpoints the causes of students' learning difficulties in CMB rather than merely describing the latter. This allows for the proposal that student-orientated CMB education on the upper secondary level could advantageously frame the educational phenomenon of cell membranes from an evolutionary viewpoint. Asking students how and why cell membranes came into being and further discern between single isolated and several collaborative compartments can, as proposed in this thesis, give students the opportunity to recontextualise, but *not* discard, their idea of rigid cell membranes, namely as a means to facilitate biological organisation. These lines of arguments give more weight to the claim (e.g., Hasni et al., 2016; Odom, 1995) that it is insufficient to learn the concepts of diffusion and osmosis in isolation. While students on the tertiary level (cf. Rundgren & Tibell, 2010; Rundgren et al., 2010) might be able to directly grapple with microscopic concepts in cell membranes, it seems that upper secondary students need to contextualise cell membranes within the mechanistic evolutionary and organism level in order to understand these concepts.

Apart from explaining and proposing what seem to be students' most relevant cognitive variables to be respected in CMB education, my PhD-project also provides knowledge about which affective variables seem to be of educational relevance. Interestingly, as in contrast to existing research (e.g., Prokop et al., 2007), my findings suggest that upper secondary students take an interest in biological concepts, namely in particular in relation to health-related issues with which students are familiar from their everyday life (e.g., cancer or nicotine consumption), but also on a broader meta-cognitive level (see also next section) that refers to the philosophy of biology (mechanisms and processes). In regard to the detailed analysis of students' conceptions as presented in this thesis, learning CMB on the upper secondary level was found to be an evolutionary process constrained by the interplay of affective, conceptual, epistemological and ontological variables. Evolutionary is here understood in the sense as proposed by Vosniadou et al. (2008), and in contrast to Posner et al.'s (1982) initial conceptual change theory where, as discussed in the theoretical framework, learning was advocated as a more radical change of conceptions tied merely to a feeling of discontent. Albeit, as found in this thesis, apparently the feeling of discontent plays an important role when students learn CMB, it seems to be of a weaker kind, namely a step-by-step process where students actively develop, but do not discard, their initial conceptions about cell membranes as material entities. Students, as found here, appear to gradually track a divergent, rather than linear, pathway (see also figure 10, article III) where they first need to understand the difference between their own and the new offered explanations (isolating and static cell membranes vs. separating and dynamic cell membranes), before they consider and then eventually accept the plausibility and fruitfulness of the latter. That means, students seem to iteratively return to and use their initial conceptions about CMB when the new explanations lack coherence according to their developing conceptions. Such learning procedures are also similarly described when lower and upper secondary students learn molecular genetics, (e.g., Knippels & Waarlo, 2018; Lewis & Kattmann, 2004; Marbach & Stavy, 2000; Venville & Treagust, 1998) and evolution (e.g., Baalmann & Kattmann, 2001; Zabel & Gropengießer, 2011), concepts both relating to biological processes. In their complex study examining 10th grade students' learning processes in genetics according to epistemological, ontological and affective conceptual change perspectives, Venville and Treagust (1998) concluded that genetics learning seems to involve a "process of raising the status of more scientifically adept models of genes which are reconcilable with less adept models of genes" (p. 1052), which combines weaker forms (understanding genes as active instead of passive particles) with stronger ontological conceptual developments ("active particle gene" to "sequence of instructions gene", p. 1052). Even though more research is needed to provide a more detailed understanding of students' learning processes in CMB, it can appear that, similarly, students' conceptual development of cell membranes as separating and organising barrier seems to be of a weaker kind than their development towards cell membranes as supra-molecular processes which are open to their surrounding environment.

While this section discussed students' knowledge at stake when learning CMB at the upper secondary level and contextualised it within comparable prior research, the following section discusses how such knowledge is useful in order to select or design teaching strategies and tools more specifically according to students' needs along with assessing students' conceptual understanding.

6.1.3 Design and evaluation of teaching and learning strategies

This section casts a closer glance at the usefulness of analogies as an overall teaching strategy for CMB learning and thereby discusses issues which can be of interest for the MLS community in general.

This thesis supports the view (Venville & Treagust, 1996; Vosniadou et al., 2008) that analogies, instructional as well as student-generated, can provide a powerful overall teaching strategy to foster evolutionary learning processes, such as the above-described process of CMB learning, as long as certain design aspects are taken into account. In this thesis, analogies as constructivist strategy to highlight comparisons between the concrete already known and the abstract new, have informed the design of different kinds of verbal and visual teaching tools such as thought experiments, spatial models, and everyday examples which have been found to be beneficial for learning science in general (Harrison & Treagust, 2006; Niebert et al., 2013; Wilbers & Duit, 2002) and MLS specifically (Anderson & Schönborn, 2008; C. Johnson & Luft, 2001; Venville & Treagust, 1996; Verhoeff et al., 2008). My research is in this regard also an indication that combining several modes of language (Prain & Waldrip, 2006) (visual, spoken, and tangible) along with offering more than one visualisation of the same concept (e.g., Gilbert & Treagust, 2009; Kozma, 2003) appear to be powerful strategies to enhance students' understanding of complex scientific concepts. However, a critical affordance for the usefulness of the teaching tools as employed in this thesis appears to be that they are clear and precise in their design; to ensure that they are understood by students in the intended way (Rundgren & Tibell, 2010); for instance not simply highlighting literal “surface similarities” (Duit, 1991, p. 659) (e.g., the shape of lipids and candies), but rather more complex, functional ones (e.g., the colours of candies and lipids’ amphiphilic structure). To that end, it seems critical that the message(s) instructional analogies are meant to convey are iteratively reconstructed one at a time. In that way they can tell a coherent narrative (e.g., how the different compartments in houses can be connected) by means of providing potential explanations at the same time as they open up for further questions (Knippels & Waarlo, 2018) which cast new light on the analogies already used or make necessary the invention of new analogies. If such learning is to be successful, it needs, according to the findings of this thesis, to be scaffolded by cooperative learning environments, such as small student groups allowing students to discuss CMB in their own language along with feeling comfortable to utter insecurities (Kersting et al., 2018; Lemke, 1990). Hence, the view advocated here is that the usefulness of analogies as a teaching strategy seems highly constrained by both external variables (e.g., cooperative learning environments and appropriate guidance by the teacher), the design of the analogy-based tools and students’ internal variables, such as their ability to construct the intended linkage between concrete source and abstract target (cf. Krüger, 2007; Schönborn & Anderson, 2008b). When the interplay of these variables is provided, it seems that the particular usefulness of analogies in enhancing evolutionary learning processes seems to be their ability to make explicit students’ intuitive ontological and epistemological assumptions; by means of linking the unfamiliar to the familiar, but also by provoking discontent in terms of contrasting students’ conceptions (cf. Duit, 1991; Wilbers & Duit, 2002). As already proposed elsewhere (e.g., Kapon & DiSessa, 2012; Kersting, 2019; Wilbers & Duit, 2002), this seems due to analogies’ ability to sensitise students to the more general scientific practice of continuously testing, problematising and refining conceptions, and the specific biological practice of observing and exploring mechanistic-and process-based experiences. In the case of CMB learning specifically, learning with analogies appears, for example, to help visualise for students the scientific processes which eventually led to the proposal and continuous refinement of the fluid mosaic model (cf. C. Johnson & Luft, 2001). In corroboration of prior research (e.g., Harrison & Treagust, 2000) my findings indicate in this regard that analogies seem to have the potential to “bridge between cognitive and affective domains of learning” (Duit 1991, p. 653), amongst others, because students seem to enjoy using them.

Outcomes regarding the applicability of analogies as overall teaching strategies and different kind of visualisations as teaching tools are largely consistent with the prior research discussed here. However, what distinguishes the here proposed educational approach from other CMB-related approaches (e.g., Gregers & Suhr Lunde, 2021; Lue Leh Ping et al., 2020; Rundgren & Tibell, 2010; Verhoeff et al., 2008) is the stronger emphasis on the interrelation between experiences, language, and conceptions. Existing approaches seem concerned with visualising cellular processes as they are in “reality”, such as in computer-simulated animations (e.g., Noroozi & Mulder, 2017; Rundgren & Tibell, 2010; Sanger et al., 2001) or very detailed scale models of cells (Verhoeff et al., 2008). Supporting existing proposals (e.g., Baalmann & Kattmann, 2001; Riemeier & Gropengießer, 2008) my approach emphasises, however, the feasibility of precisely identifying the scope of educational language, which due to its ambiguity can limit students’ learning processes (in the case of CMB: e.g., barrier, separation, environment and protection), and subsequently specify and highlight concrete everyday experiences as abstractions of the biological functions and structures to be understood. The *fat droplet activity*, for example, appears rather far-fetched and too simplified from a biological viewpoint because it does neither show intra- or intercellular environments nor transport processes at cell membranes. However, viewing it from students’ viewpoints it is rather complex because it highlights what appears extremely difficult for students to understand: how fatty molecules *eventually* came to form spherical bubbles which separate different aqueous environments from each other.

Based on the considerations discussed here, this thesis contributes with knowledge regarding how students' conceptual understanding in CMB can be assessed. Learning CMB, as discussed above, was in thesis found to be determined by the interplay of different internal (conceptions, interests, and motivation) and external variables in the context of a reconstructed social and cultural framework. In the introduction, I introduced conceptual understanding as a recontextualisation of socially shared concepts. In the course of conducting my research, this definition could be specified. According to my findings, it falls short if students' conceptual understanding is assessed only as a measurement of an increased usage of scientific terminology as, for example, emphasised by Norwegian curricula guidelines (e.g., Utdanningsdirektoratet, 2021a) because the meaning students associate with this can differ greatly from scientists associated meaning. Rather, it can look as if students' conceptual understanding of CMB can be assessed as a transfer from a passive to a more active usage of, from educational viewpoint adequate, scientific *and* everyday language. In contrast to Haug and Ødegaard (2014), who seem to speak of conceptual understanding as a transfer of spoken language ("word knowledge") (p. 777), and in specification of what was discussed in article III, I would now argue that this transfer should also refer to other modes of language (symbols, depictions, statements, etc.). More specifically, a conceptual understanding of CMB appears to become visible as a process where students associate old (e.g., proteins or lipids) and new terms (e.g., compartments) along with visual models with a new meaning (Gropengießer, 2007; Groß et al., 2020; Lakoff & M. Johnson, 1980) in the course of recontextualising these within to them coherent functional evolutionary and organism-related explanations (e.g., how proteins relate to students' health). In line with this specification, it is suggested here that conceptual understanding in CMB should not only be assessed according to a development in spoken and written language, but also in practical skills (such as to actively model the fluid mosaic model), and attitudes (increasing interest in how mechanistic explanations relate to macroscopic personal and social phenomena) (cf. Schönborn & Anderson, 2009, 2010). This consideration gives more weight to Zohar and Ginossar's (1998) and Kattmann's (2007a) claim that students' anthropomorphic and teleological explanations are not necessarily illegitimate for their conceptual understanding in biology—because they do not necessarily reflect anthropomorphic and teleological *reasoning*. When, for example, teleological explanations are not used to postulate biological functions as a means to fulfil a purpose (as when students describe cell membranes structures as means to protect cells or Galen described the functionalities of the human body), but rather describe the functional attributions of structures or processes (e.g., why cell membranes have a lipid bilayer structure), they should be valued as legitimate explanations in biology education as they can help students make highly abstract phenomena less abstract (Nagel, 1961; Zohar and Ginossar, 1998).

I want to conclude this section by saying that it is exciting that recent findings from the realms of cognitive linguistics and psychology have the potential to inform CMB education. As my research has provided first examples of how facets of cognitive linguistics can be productively used in the context of CMB education, I suggest to employ this approach as an interpretive framework for future MLS studies investigating learning and teaching with analogies and other kind of visualisations.

6.2 Summing up my approach of an educational reconstruction

Summing up my approach to an educational reconstruction of CMB, its contribution lies not in the proposal of a readily designed learning environment, but rather a detailed identification, description and scrutiny of the different variables at stake when planning and conducting upper secondary CMB learning and teaching. This PhD-project suggests CMB education in this regard as a complex field constrained by the mutual selection of relevant scientific ideas structuring the content of teaching and student ideas as preconditions for learning. In combination, these ideas inform the formulation of learning goals as precise statements concerning what students should be able to understand and do, during and after teaching. Moreover, do they influence the selection or design of adequate teaching strategies and tools guiding students on how they can reach these goals. It follows that science educators' responsibility seems to lie in creatively and reflectively linking these different components to each other (Baalmann & Kattmann, 2001; Duit et al., 2004; Schön, 1983) while at the same time giving responsibility to their students to actively engage in learning processes. Rather than using existing CMB content, teaching strategies or tools uncritically, my PhD-project wants to invite other researchers and educators to employ the findings produced here as a starting point to stop and think: about what might be essential ideas for students to understand about CMB and how these relate to their conceptions, interests and everyday life. It seems that upper secondary students become reflective learners in the field of CMB only when they are allowed to take command of their own learning processes; that is themselves construct knowledge according to new experiences rather than adopting scientists' experiences or being served knowledge by their teacher (Driver, 1989; Hasni et al., 2016; Polanyi, 1966; Wagenschein, 1968/1999).

In line with these considerations, my findings legitimise the empirical identification and investigation of student conceptions as fundamental part of modern MLS education research—about 40 years after its constructivist-informed implementation (Duit, 1996). However, in light of my findings it seems necessary to specify that we need sound efforts to qualitatively describe and explain students' conceptions not only after, but especially before and during, instruction. As exemplified in this thesis, this could be achieved by combining educational theories with notions from cognitive linguistics along with employing process-based methods and designs (Baalmann & Kattmann, 2001; Gregers & Suhr Lunde, 2021; von Aufschnaiter, 2014). In this respect, it appears misleading to promote one's research as means to investigate students' conceptual understanding when multiple choice questionnaires are employed as the main method to collect students' conceptions (e.g., Lue Leh Ping et al., 2020): It is assumed that students have an understanding of ideas similar to that of the researcher. Moreover, this thesis supports the argument that more (self)-critical dialogues between MLS and educational researchers (cf. Pickersgill, 2020) are necessary in order to bridge between theory and practice. According to my research, these critical dialogues should, along with existing curricula content, guide the aims and scope of educational MLS research.

In this regard, McIntyre (2005) proposes three main criteria for how educational research can successfully contribute to building bridges between theory and practice:

- research should generate valid new understandings of the realities of classroom teaching and learning;
- these new understandings should provide a basis for clear indications to classroom teachers concerning how they might be able to improve their practice;
- the new understandings, and suggestions for improvement to which they lead, should make sufficient sense to teachers to persuade them to take the suggestions seriously and so engage in dialogue about them (p. 380).

Using these criteria as backdrop for the outcomes of my PhD-project, clearly a necessary next step must be collaboration with teachers (see next section) in order to iteratively test and further develop my approach according to real classroom settings. However, I think that theoretical framework, methods and outcomes of this thesis should justify just as much as legitimate approach to inform the reconciliation of educational research and classroom practice (Hand et al., 2020) because it illuminates critical aspects (such as everyday-related conceptions) which might be more obscured when conducting research in real classrooms. In proposing an interdisciplinary approach which attempts to maintain closeness to both the mother discipline and educational realms, my hope is thus that my research can contribute to the development of practice rather than a “distraction” from it (Schön, p. ix)

6.3 Methodological considerations

The research questions put forth in this thesis offer a broad variation of potential design and methods. Chapter 4 served to discuss and clarify coherence between background, motives, research questions, theory and the ultimately chosen design and methods in this thesis (Maxwell, 2013; Wackerhausen, 2017). It was in this respect argued that the project's research questions make particular epistemological and ontological demands that can only be fulfilled by some designs and methods.

In line with the philosophy of educational reconstruction as proposed by the MER (Duit et al., 2012), the final choice fell, therefore, on an approach in between applied and basic approaches of science education research positioned within overall interpretive research. This was justified with the aim of my PhD-project to provide theoretical- and empirical-based detailed descriptions and explanations of core ideas and learning processes rather than outcomes ready to be used in classrooms. Discussing the applicability of the MER's approach to an educational reconstruction at a time where educational responsibilities along with the quantum of scientific knowledge increases, has been emphasised as the critical future task of the MER community (amongst other in the seminar I was referring to earlier). In the theoretical framework I have sketched the MER as a holistic framework which, rooted in Bildung movements and constructivist ideas, wants to be a practical theory which provides guidance for classroom-relevant educational research (Duit et al., 2012; Kattmann et al., 1997). According to the outcomes of this thesis, as were discussed in the previous chapters, the particular service of the MER for modern science education research seems to be its emphasis on precisely analysing "the knowledge at stake" (Méheut, 2014, p. 610). In this way, it provides a useful alternative to either replace students' erroneous conceptions with scientific conceptions, which can be the impression of some MLS approaches (e.g., Gregers & Suhr Lunde, 2021; Howitt et al., 2008), or give considerable responsibility to students with regard to themselves form teaching based on self-defined problems as, for example, proposed as a popular possibility to learn genetics (Knippels & Waarlo, 2018). In contrast to the problem-posing approach or

Wagenschein's (1968/1999) proposal of exemplary teaching, the aim, context and relevance of a teaching sequence is in this thesis primarily guided by the reconstructed scientific content as a means to define the essential ideas (cf. Klafki, 1969) students should understand (e.g., discern between separation as isolation and separation as compartmentalisation) while the societal contextualisation is first elaborated in the course of teaching (e.g., to understand how cell membranes relate to personal and social health issues).

I experienced the here described procedure of educational reconstruction as a rather time-consuming and challenging strategy which made high demands on issues of trustworthiness and authenticity (see chapter 4). However, my findings give reason to believe that using this time is worthwhile in order to ensure that the knowledge produced withstands the high demands of modern science education. Rather than wanting to claim that only one approach of educational reconstruction is the "right" one, I want to argue that the suitability of an employed approach depends on the design and questions asked. When, as in my project, the motivation for conducting educational design research is to empirically illuminate different facets of a rather new and abstract area of science, then the MER appears a very feasible framework (cf. Kersting et al., 2018; Laherto, 2012). If the aim is to produce findings ready to be employed in classrooms, it can appear that the MER has shortcomings compared to other design frameworks. Teaching experiments in their original form together with other design experiments (Cobb et al., 2003) or other DBR approaches seem more suitable for such research in terms of providing guidance of formulating clearer design hypotheses (cf. Kersting et al., 2018) to be used in iterative rounds of data collection in collaboration with teachers and larger student populations and researcher networks (McKenney & Reeves, 2012).

My findings indicate in line with prior general educational (Darling-Hammond, 2000) and specific MLS research (e.g., Knippels & Waarlo, 2018) that teachers play a critical role as facilitators in modern student-orientated science education. However, although teachers seem to think along constructivist lines when planning and carrying out their lessons at the same time as seeming motivated to develop their classroom practices (e.g., Lysberg & Rønning, 2021), research also indicates that their own way of thinking is not always in line with the ideas of educational reconstruction (Abell, 2007; Borko, 2004). Collaborating with teachers who seem to become more committed to changing existing practices when their views are taken into account and when they are scaffolded by cooperative teams (Fullan, 2005; Lysberg & Rønning, 2021) seems thus a crucial step towards sustainably developing the learning environment as proposed in this thesis. Accordingly, it could be interesting to combine the methods used here with a set of different methods that have shown useful in existing educational research: such as the observation of students' collaborative discourse in classrooms when interacting with the learning environment (e.g., Kersting et al., 2018) or a quantification of students' conceptions. An interesting approach could in this regard also be to explore how students communicate modern biology when no teacher or researcher is listening. While this research did not venture in this way, what I heard the participating students discussing during the breaks between teaching, regarding mainly the origin of cell membranes, seemed worth knowing more about. Afterall, the aim of education, as put forth in this thesis, should be that students take what happens in the classrooms with them to their outside everyday life.

In line with the epistemological and ontological assumptions framing this thesis, my aim was not to draw general conclusions about whole populations, but to produce knowledge transferable to other relevant contexts (see also section 4.5). Hence, the results and conclusion as discussed in the following chapter are not fixed, but are meant to open up for inspiration, new interpretations, possibilities and questions. Fruitful CMB learning and teaching on the upper secondary level, as it can be viewed from this thesis, requires the interplay of research-based knowledge with a thorough theoretical foundation and teachers' practical expertise.

7 Conclusions

Reflecting the characteristic nature of the field of biology education concerned with bridging between the mother discipline and educational realms, and the assumptions of an interpretive paradigm, this thesis ventured into a theoretical- and empirical-based exploration of the processes necessary to turn the scientific theory of CMB into a teachable area for upper secondary education. By means of investigating the molecular mechanisms of biological processes, MLS has turned into a key scientific discipline in regard to facing the societal challenges of the 21st century. While the knowledge it produces increasingly impacts our daily life by means of proposing technological advances and influencing personal and social lifestyle and sustainability decisions, it becomes at the same time more and more abstract and less accessible for the general public and education. Realising the educational opportunities and responsibilities of MLS, the MLS education community occupies itself with finding ways to select content they deem necessary for school students to understand and to find teaching and learning strategies which address this content meaningfully (e.g., Mc Ewen, 2021; Tibell & Rundgren, 2010). Taking into account these developments, my thesis contributes through a sequence of three substudies which were synthesised in this kappe document, to the world of educational scholarship and practice as follows:

a) I have conducted research within an interpretive paradigm that investigates and deepens our understanding about how scientists and students think in the domain of CMB and how this understanding can be used to select scientific core ideas in ways students may understand them.

b) I have constructed a learning environment that proposes a way to fruitfully teach and learn these core ideas on the upper secondary level by means of empirically and theoretically scrutinising and exploring the different variables at stake when teaching and learning CMB in classroom-similar settings.

While theoretical and practical implications of my work along with recommendations for future research will be discussed in the following section, this section summarises and elaborates on the most important contributions of this PhD-project within a national and international research context. This is done along the three dimensions of *why*, *what* and *how*.

School curricula are limited in time and resources and cannot cover all the topics scientists immerse themselves in. Wagenschein (1968/1999) claims in this context that we must free schools from being a service machine; the older a subject, the stricter its educational structure; the simple first, then the complicated, leaving students anxious about what is to come next. The outcomes of my PhD-project give weight to the argument (e.g., Leach & Scott, 2002) that research-based knowledge is necessary if the aim is to shape and improve MLS as a field of school education, in this case CMB education, in a way that makes it seem worthy and exciting to understand for students and manageable by teachers.

My research concludes that we need interdisciplinary approaches that along the lines of an interpretive paradigm illuminate several aspects at stake when the aim is to offer student-orientated education in the realms of modern biology. For example, reconstructing students' and scientists' perspectives as a dynamic interplay between cognition, language and experience according to their social and cultural context, is valuable in order to create an awareness that the aims of education cannot be guided by what appears to be scientifically correct, but rather by what is applicable from an educational viewpoint, balancing between oversimplification and detailedness (cf. Kattmann, 1997). This view challenges existing research approaches labelled with a constructivist stamp, at the same time as scientific correctness seems to guide their search for the aims of education (e.g., Howitt et al., 2008; Lue Leh Ping et al., 2020). Following these lines of thinking, the outcomes of my study suggest that content selection above all must be framed by the question *why* students should learn a certain topic because it can help educators define students' needs and subsequently specify learning goals, which take into account what students find challenging to understand (cf. Schönborn & Anderson, 2008a). According to my findings, I think that CMB should be considered as an educational significant field with regard to three universal points of view:

1. In discussing the biological processes of cell membranes students can embark on an exciting journey back to the time when life started. CMB as a starting point to think about what differentiates us from other species, but more importantly what unites us with them, is, as I see it, crucial in regard to what has been claimed to be the unique responsibility of biology education: to contextualise human life within the life of others (Reiss & White, 2014). In that way, students could be sensitised to questions of sustainability, which across the world are being encouraged as one of the core elements in all education (Lehrplan 21, 2016; UNESCO, 2021; Utdanningsdirektoratet, 2021c).
2. Exploring and explaining how cell membrane structure relates to functional processes on the organism level allows students to gain a better grasp of the abstract realms of their own body's functioning. In contrast to prior research (e.g., Venville & Treagust, 1998), my findings indicate that students are interested in microscopic explanations; however, these must clearly relate to relevant personal and social aspects, such as understanding how their own handling affects their and others' lifestyle. My hope is in this respect that my approach contributes to ongoing international (McComas et al., 2018; Prokop et al., 2007) and national Norwegian (e.g., Gregers & Suhr Lunde, 2021; Ludvigsen et al., 2015) discussions concerning how we can make modern biology more useful and interesting for students.
3. Engaging students in the more general realms of biological practice as a potential to foster their understanding of science content is an argument that the MLS education community has repeatedly advocated (e.g., Hasni et al., 2016; Verhoeff et al., 2008). The territory of CMB offers in this regard sound

possibilities for students to venture into the philosophy of (biological) science and consequently enable them to more critically scrutinise what is presented as scientific facts—in their everyday life as well as in teaching situations.

Apart from producing knowledge which contributes to a deepened understanding of what should be the greater goals in the domain of CMB education aiming at fostering students' general curiosity about and understanding of modern biology, this thesis also contributes with useful insights into what students should learn specifically in this domain and how they can learn it. In emphasising and contextualising the scientific core ideas of *compartmentalisation* and *multicellular coordination* as means of (increased) biological organisation and dynamic openness between environments, my research contributes with new findings regarding a research-based proposal of content structure and learning goals specifically for the upper secondary level. This is significant as a distinction from proposals for the tertiary (e.g., Howitt, 2008, Rundgren et al., 2010) and lower secondary level (e.g., Gregers & Suhr Lunde, 2021), along with a clearer student-orientation than existing approaches for the upper secondary level is highlighted (e.g., Lue Leh Ping et al., 2020; Rundren & Tibell, 2010).

By means of empirically scrutinising and developing analogies as an overall teaching strategy to visualise aspects found critical to understand CMB on the upper secondary level, this thesis makes important theoretical and practical contributions not only of use for the CMB community, but also the MLS community in general. While the trend at the tertiary (e.g., Norrozi & Mulder, 2017), and partly also the secondary level (e.g., Rundgren & Tibell, 2010), seems to go towards the investigation of digital teaching tools as resources for students' learning processes, the approach employed here pursues another direction. Namely, it seems that teaching tools which to a lesser extent visualise the "real" biological processes of cell membranes, but to a greater extent emphasise more concrete everyday experiences (like the behaviour of vegetable oil in water), can be just as valuable for the promotion of students' learning processes. Fostering students' learning processes as teachers is, according to the findings of my thesis, tied to being able to understand and assess different facets of students' conceptual understanding.

The MLS community intensively attempts to find answers to what understanding a concept might mean (cf. Anderson & Schönborn, 2008; Duncan & Reiser, 2007; Schönborn & Anderson, 2008a). My findings contribute in this regard by specifying that conceptual understanding should not only be tied to a transition of students' spoken language from a passive to a more active command, but also their *doing* along with the development of values and attitudes (Lemke, 1990; Schönborn & Anderson, 2008a, 2010). This seems to challenge some educators' viewpoint who appear to tie conceptual understanding solely to students' command of word knowledge (cf. Haug & Ødegaard, 2014; Kersting et al., 2018).

As this PhD-project contributes with further developing our theoretical and practical understanding of the topic of CMB, it legitimises MLS education research in general as a complex area of science education which needs more research, but also more dialogues between scientists, educational researchers, policymakers and practitioners.

7.1 Implications

This thesis illuminates aspects of teaching and learning CMB that have practical and theoretical implications within several dimensions of biology education. In the following I focus on two of them which I think are the most critical ones, namely the organisation of biology curricula and facets of teacher education and their professional development. Special attention is given to the Norwegian context where my data were gathered.

My research gives weight to curriculum developers' and policymakers' argument that contemporary biology education should more than ever emphasise biological processes rather than cover numerous unrelated concepts (Ludvigsen et al., 2015; Schreiner & Sjøberg, 2004).

In clearly illustrating CMB as an inter-and intradisciplinary educational phenomenon, my research prompts curriculum developers not only pinpoint interdisciplinary content as done by recent Norwegian curricula revisions, but also clearly manifest platforms for teachers to collaborate in between disciplines and subjects (cf. Mohlhenrich, 2021). Based on these considerations, it is not recommended that evolution, genetics, cell biology and so on are distributed to different courses for students to choose from, as is the case in Norwegian upper secondary biology curricula (Utdanningsdirektoratet, 2021a, b). Moreover, it seems critical to specify learning outcomes in curricula according to content (what students should understand), skills (what they should be able to to) and attitudes (values and interests students should develop).

If the here discussed content, teaching tools and strategies indeed are promotive for students' learning processes on the upper secondary level, then it is necessary to more explicitly implement and teach meta-cognitive skills, like interpreting visualisations and engage in inquiry-based discussions in biology curricula. Moreover, in light of my findings, it is doubtful if traditional teaching methods, for instance light microscopy, traditional designs of contemporary educational textbooks (such as the distinction between cell prototypes) or surface analogies as they often seem appear applied in upper secondary classrooms (e.g., mitochondria as powerplants), are still up-to date—at least when they are not scaffolded by a clear rationale (cf. J. Nelson, 2012) or alternative tools are provided. Since textbooks are vital resources for students' learning processes in science (Tulip & Cook, 1993), with teachers often heavily relying on them (J. Nelson, 2012), it is thus crucial that these are refined in line with recent curricula recommendations and the findings of this thesis, namely the emphasis on biological processes.

Outcomes of this project indicate that biology teachers' role is multifaceted and might even be the most important factor with regard to student achievement (cf. Hasni et al., 2016). My findings suggest that rather than being experts within a specific scientific field, pre-service biology teachers should be educated to become experts on understanding and assessing students' conceptions about a certain topic, on the one hand, and be well-acquainted with the idiosyncratic scientific character of this topic on the other (cf. Wild & Krapp, 2001). Such an acquaintance requires understanding the societal relevance of the content at stake, taking interest in the questions it asks and, importantly, critically scrutinising content, learning goals and teaching strategies as proposed in school textbooks and science curricula in order to contextualise these in a way they make sense for students (cf. Komorek & Kattmann, 2009; Wilbers & Duit, 2002). To achieve this, it seems critical that in teacher education, scientific content is continuously related to educational *and* psychological knowledge and that teacher education programmes actively bridge between the necessary academic and practical education of teachers. It can in this regard be useful to, for example, provide pre-service teachers with a clear rationale what they should consider and look at when practicing teaching biology at schools (cf. van Dijk & Kattmann, 2007).

If, furthermore, in-service teachers are to become active curriculum developers and reflective practitioners (Duit et al., 2004; Schön, 1983) who are concerned with continuously questioning and improving existing teaching practices, it seems necessary that they in the same way as their students are provided with sufficient scaffolding, such as time, space and cooperative groups (Lysberg & Rønning, 2021; Merritt, 2016). To stay ahead of the rapid developing biology content they are teaching, it appears furthermore vital that in-service teachers take part in further disciplinary training courses on a regular basis—in the same way as science education researchers and scientists should more actively seek the dialogue with schools and teachers.

The outcomes of this thesis show that assessing students' conceptual understanding is a critical, albeit difficult variable in student-orientated MLS education. While there is consensus in the MLS education community that teaching for conceptual understanding is the aim, both in Norway (e.g., Gregers & Suhr Lunde, 2021; Ludvigsen et al., 2015) and worldwide (e.g., Howitt et al., 2008; Konicek-Moran & Keeley, 2015), there seems to be a tension between a simultaneously increasing demand to make teaching and learning more effective. A possible solution could be the design and further development of concept inventories. Especially in physics education, these have proven highly valuable in terms of providing useful information for both teachers and learners regarding the latter's learning progresses and difficulties (Richardson, 2005). As also internationally suggested for tertiary MLS education (Howitt et al., 2008; Smith et al., 2008) and general upper secondary biology education (Garvin-Doxas & Klymkowsky, 2008) they might be a promising alternative for upper secondary MLS education to widely applied multiple choice tests.

7.2 Recommendations for future research

To conclude this chapter, I provide an outlook on the most important future research areas that in the course of discussing and concluding my research have shown to be promising to follow up.

The outcomes of this PhD-project indicate teachers as critical facilitators for student-orientated modern biology education. Future research in this regard could examine more specifically how teachers open the door for dialogues between students and between themselves and the students in real classrooms along with investigating if and how these dialogues differ from those taking place in laboratory settings (cf. Bungum et al., 2018). This seems in particular important with regard to that, usually, teachers have to handle larger student populations which disables their ability to immerse themselves as deeply in all student dialogues as done in this thesis. To look more deeply into teachers' perspectives regarding CMB and their habits of teaching is also crucial in terms of improving existing learning and teaching practices in upper secondary biology because teachers' professional development is critical for educational development in science (Duit et al., 2012; McComas, 2018).

This study focused mainly on exploring the impact of teaching strategies and tools on groups of students. However, (science) education policymakers (e.g., Ludvigsen et al., 2015) and researchers (e.g., Aspfors, 2012; Zabel & Gropengießer, 2011) emphasise that it is desirable or even necessary to be aware of and adapt teaching methods according to the heterogenicity of student groups in order to ensure that individual students' needs are met in the best possible way. It would be beneficial in this regard if future research ventured into exploring and comparing individual students' learning processes when they work with the here proposed teaching tools. Furthermore, this work has centred on investigating the usefulness of a sequence of teaching tools on students' learning processes in CMB. Further research is needed which more specifically focusses on investigating and further developing these tools (cf. Rundgren & Tibell, 2010; Wilbers & Duit, 2002). This is necessary in order to add to and refine the critical design aspects suggested here. The outcomes of this this thesis point to the suggestion that students' learning processes are greatly impacted by affective variables (such as motivation and interests). Future research which focusses more deeply on these variables than done in this thesis could thus contribute to further developing fruitful CMB education.

Positioned within an interpretive paradigm, this project approached an educational reconstruction deeply anchored in theoretical considerations and detailed reconstructions and descriptions of students' and scientists' meaning-making processes. It could therefore be beneficial if future research could employ other designs and methods, such as such as real classroom observations combined with questionnaires, allowing for a quantification of conceptions with greater student populations and other national contexts.

In order to introduce the theory of CMB in a way that upper secondary students may understand it, this PhD-project has mainly emphasised the linkage between chemistry and biology. Clearly, a next step would be to add the realms of physics. It could be interesting to, for example, introduce students to the idea of cell membranes as batteries. This idea could then be linked to such processes as nerve transmission or cellular respiration, which are highlighted in upper secondary curricula (Utdanningsdirektoratet, 2021) at the same time as they already are well-established fields of upper secondary education research (e.g., Asshoff et al., 2020).

In the course of this thesis, I have clarified my aim to produce knowledge that is of practical value for upper secondary biology education. A natural next step to attempt increasing the practical impact of my research would in this regard be to make my findings more accessible for teachers, and to actively collaborate with them. In the near future, I plan to do both. It is in this regard my goal to use my advantage of being integrated in both Norwegian and German science education networks. For example, I intend to distribute the proposed learning environment on both relevant Norwegian and German educational platforms which are accessible for science teachers. Furthermore, I am looking forward to actively contextualising and further developing my findings within the science teacher education community of which I am a part at my university and hope that my students can benefit from the findings produced here.

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Appendices

Appendix I Consent form for participating students

Vil du delta i forskningsprosjektet *"Undervisning om celler i videregående skole"*?

Har du lyst til å bidra til at biologilærere og forskere forstår bedre hva du som elev tenker om noen emner i biologi?

Ved å delta på dette forskningsprosjektet vil du aktivt kunne bidra til å utvikle undervisningen i biologi !

Formål

Prosjektet er et **Ph.d. prosjekt** som foregår over 3 år. Formålet med prosjektet er å få innsikt i elevers forestillinger om menneskekroppen og cellene vi er bygd opp av. På bakgrunn av elevers forestillinger vil vi utvikle et **undervisningsopplegg** om cellebiologi.

Hvorfor: Det å forstå cellen er avgjørende for å forstå hvordan kroppen din fungerer; f.eks. hvordan den reagerer når man røyker, tar en Aspirin, eller spiser.

Hva innebærer det for deg å delta?

Deltakelse i prosjektet vil for deg innebære **å delta i ett individuelt intervju (på ca. 30 minutter)** i første omgang og evtl. **et undervisningsopplegg samt gruppe intervju (på ca. en halv dag)** ved en litt senere anledning. Intervjuene og undervisnigen vil enten foregå ved skolen din, eller på NORD universitet. Det vil bli gjort videoopptak av intervjuene og undervisningsopplegget. Du vil kun **være med** på disse **videoopptakene**, **dersom du samtykker til å delta på prosjektet**.

Du **trenger ikke å forberede deg** på hverken intervju, eller undervisningsopplegg på noen måte. **Dette er ikke å anse som en test, men handler om å få innblikk i dine forestillinger.**

Det er selvsagt **frivillig** å delta i prosjektet. Hvis du velger å delta, kan du når som helst trekke samtykke tilbake uten å oppgi noen grunn. Alle opplysninger om deg vil da bli avidentifisert. Det vil si at kjønn og alder vil kunne gjenkjennes, men ikke navnet ditt, hvilken skole du går på, eller hvilken by du bor i.
Det vil selvsagt ikke ha noen negative konsekvenser for deg, hvis du ikke vil delta eller senere velger å trekke deg. Det vil ikke påvirke ditt forhold til skolen/lærer.

Hva skjer med informasjonen vi får gjennom å intervjue og filme deg?

Opplysningene som vi i løpet av prosjektet vil samle inn, vil ikke bare være viktig for dette prosjektet, men også for annen forskning på feltet. Kunnskapen vil også bidra til å utvikle undervisningen for lærerstudenter. Det betyr at det kan være aktuelt å bruke data fra prosjektet i undervisningssammenheng på lærerutdanningen ved Nord Universitet, samt å dele disse på arenaer med andre forskere som f.eks. forskergrupper og konferanser.

Hvem er ansvarlig for forskningsprosjektet?

Prosjektet gjennomføres ved Fakultet for lærerutdanning, kunst og kulturfag ved **Nord universitet,** Bodø. Vi samarbeider også med Otto-Friedrich-Universitaet i Bamberg (Tyskland).

Hvorfor får du spørsmål om å delta?

Siden prosjektet handler om videregående elever sine forestillinger om celler, er det helt avgjørende for prosjektet at **motiverte elever fra videregående skole** har lyst til å delta. Utvalgskriterier er nettopp at du går på **Videregående Skole, har valgt biologi som programfag i utdanningsprogram for studiespesialisering, og at du er motivert til å delta.** Hele klassen din vil få denne forespørselen.

Ditt personvern – hvordan vi oppbevarer og bruker dine opplysninger

Vi vil bare bruke opplysningene om deg til formålene vi har fortalt om i dette skrivet.

- Det er ph.d.-kandidaten Leonie Johann som vil være ansvarlig til å samle, bearbeide, lagre og analysere data. Prof. Steen Wackerhausen fra Nord Universitet samt Prof. Jorge Groß fra Otto-Friedrich-Universitaet Bamberg (Tyskland) vil også få innsikt i data. Det vil også være aktuelt at deltakere av forskningsgruppene i Bamberg og på Nord Universitet får innsikt i data. Alle opplysninger om deg vil da bli avidentifisert, det vil si at du ikke vil være gjennkjennbar annet enn gjennom kjønn og alder.
- Datamaterialet vil bli sikret med brukernavn og passord slik at ingen ellers får tilgang til det.

Hva skjer med opplysningene dine når vi avslutter forskningsprosjektet?

Prosjektet skal etter planen avsluttes i august 2021. Etter prosjektslutt ønsker vi å oppbevare videoopptakene. Disse vil bli lagret på maskinvare tilhørende NORD Universitet og vil krypteres (**dvs informasjonen kan ikke leses av uvedkommende**) under lagring.

Lagring av data er viktig i forskningen for å ha muligheten til etterprøving, samt til å evt. kunne gjennomføre oppfølgingsstudier. Videopptakene vil bli lagret 10 år frem i tid.

Dine rettigheter - Vi behandler opplysninger om deg basert på ditt samtykke.

Så lenge du kan identifiseres i datamaterialet, har du rett til:

- innsyn i hvilke personopplysninger som er registrert om deg,
- å få rettet personopplysninger om deg,
- få slettet personopplysninger om deg,
- få utlevert en kopi av dine personopplysninger og
- å sende klage til personvernombudet eller Datatilsynet om behandlingen av dine personopplysninger.

På oppdrag fra Karin Lillevold har NSD – Norsk senter for forskningsdata AS vurdert at behandlingen av personopplysninger i dette prosjektet er i samsvar med personvernregelverket.

Hvor kan jeg finne ut mer?
Hvis du har spørsmål til studien, eller ønsker å benytte deg av dine rettigheter, ta kontakt med:

- Leonie Johann*, leonie.johann@nord.no* ved NORD Universitet, eller Steen Wackerhausen*, steen.wackerhausen@nord.no*
- Vårt personvernombud (personvernombud@nord.no)
- NSD – Norsk senter for forskningsdata AS, på epost (personverntjenester@nsd.no) eller telefon: 55 58 21 17.

Med vennlig hilsen

Prosjektansvarlig

Eventuelt student

(Forsker/veileder)

Se neste side

Samtykkeerklæring

Jeg har mottatt og forstått informasjon om prosjektet *Undervisning om celler* og har fått anledning til å stille spørsmål.

☐ Jeg samtykker herved til å delta i prosjektet.

Dette innebærer at

- Du har lyst til å delta i intervju ved din skole eller NORD universitet dokumentert via lyd-og videoopptak.
- Du har lyst til å delta i et undervisningsopplegg samt intervju ved din skole eller NORD universitet som dokumenteres via videoopptak.
- opplysninger om deg publiseres slik at du ikke kan gjenkjennes [alder og kjønn vil ikke anonymiseres, mens du vil få et pseudonym og det vil ikke bli klart hvilken skole du går på, heller ikke hvilken by du er fra]
- at dine opplysninger behandles frem til prosjektet er avsluttet, ca. sommer 2021
- at dine personopplysninger lagres etter prosjektslutt [til etterprøvbarhet samt til evt. oppfølgingsstudier samt arkivering for senere forskning.]

(Signert av prosjektdeltaker, dato)

Appendix II Response from NSD

Digital Melding 03.06.2019 12:38

Det innsendte meldeskjemaet med referansekode 339478 er nå vurdert av NSD. Følgende vurdering er gitt: Det er vår vurdering at behandlingen av personopplysninger i prosjektet vil være i samsvar med personvernlovgivningen så fremt den gjennomføres i tråd med det som er dokumentert i meldeskjemaet med vedlegg den 03.06.2019, samt i meldingsdialogen mellom innmelder og NSD. Behandlingen kan starte.

MELD VESENTLIGE ENDRINGER
Dersom det skjer vesentlige endringer i behandlingen av personopplysninger, kan det være nødvendig å melde dette til NSD ved å oppdatere meldeskjemaet. Før du melder inn en endring, oppfordrer vi deg til å lese om hvilke type endringer det er nødvendig å melde:

nsd.no/personvernombud/meld_prosjekt/meld_endringer.html

Du må vente på svar fra NSD før endringen gjennomføres.

TYPE OPPLYSNINGER OG VARIGHET
Prosjektet vil behandle alminnelige kategorier av personopplysninger frem til01.08.2021. Data med personopplysninger oppbevares internt ved behandlingsansvarlig institusjon for forskning frem til 31.08.2030. Dette er i tråd med samtykke fra de registrerte.

LOVLIG GRUNNLAG
Prosjektet vil innhente samtykke fra de registrerte til behandlingen av personopplysninger. Vår vurdering er at prosjektet legger opp til et samtykke i samsvar med kravene i art. 4 og 7, ved at det er en frivillig, spesifikk, informert og utvetydig bekreftelse som kan dokumenteres, og som den registrerte kan trekke tilbake. Lovlig grunnlag for behandlingen vil dermed være den registrertes samtykke, jf. personvernforordningen art. 6 nr. 1 bokstav a.

PERSONVERNPRINSIPPER
NSD vurderer at den planlagte behandlingen av personopplysninger vil følge prinsippene i personvernforordningen om:

- lovlighet, rettferdighet og åpenhet (art. 5.1 a), ved at de registrerte får tilfredsstillende informasjon om og samtykker til behandlingen

- formålsbegrensning (art. 5.1 b), ved at personopplysninger samles inn for spesifikke, uttrykkelig angitte og berettigede formål, og ikke behandles til nye, uforenlige formål

- dataminimering (art. 5.1 c), ved at det kun behandles opplysninger som er adekvate, relevante og nødvendige for formålet med prosjektet

- lagringsbegrensning (art. 5.1 e), ved at personopplysningene ikke lagres lengre enn nødvendig for å oppfylle formålet

DE REGISTRERTES RETTIGHETER

Så lenge de registrerte kan identifiseres i datamaterialet vil de ha følgende rettigheter: åpenhet (art. 12), informasjon (art. 13), innsyn (art. 15), retting (art. 16), sletting (art. 17), begrensning (art. 18), underretning (art. 19), dataportabilitet (art. 20).

NSD vurderer at informasjonen om behandlingen som de registrerte vil motta oppfyller lovens krav til form og innhold, jf. art. 12.1 og art. 13.

Vi minner om at hvis en registrert tar kontakt om sine rettigheter, har behandlingsansvarlig institusjon plikt til å svare innen en måned.

FØLG DIN INSTITUSJONS RETNINGSLINJER

NSD legger til grunn at behandlingen oppfyller kravene i personvernforordningen om riktighet (art. 5.1 d), integritet og konfidensialitet (art. 5.1. f) og sikkerhet (art. 32).

Transkriptør er databehandler i prosjektet. NSD legger til grunn at behandlingen oppfyller kravene til bruk av databehandler, jf. art 28 og 29.

For å forsikre dere om at kravene oppfylles, må dere følge interne retningslinjer og/eller rådføre dere med behandlingsansvarlig institusjon.

OPPFØLGING AV PROSJEKTET

NSD vil følge opp underveis (hvert annet år) og ved planlagt avslutning for å avklare om behandlingen av personopplysningene er avsluttet/pågår i tråd med den behandlingen som er dokumentert.

Lykke til med prosjektet!

Kontaktperson hos NSD: Karin Lillevold

Behandlingen av personopplysninger er vurdert av NSD. Vurderingen er: NSD har vurdert endringen registrert 03.06.2021.Vi har nå registrert 31.10.2021 som ny sluttdato for forskningsperioden. Data med personopplysninger oppbevares internt ved behandlingsansvarlig institusjon for forskning frem til 31.08.2030. Dette er i tråd med samtykke fra de registrerte. NSD vil følge opp underveis (hvert annet år) og ved ny planlagt avslutning for å avklare om behandlingen av personopplysningene er avsluttet/pågår i tråd med den behandlingen som er dokumentert.

Kontaktperson hos NSD: Karin Lillevold. Lykke til videre med prosjektet!

Part II

Article I

education sciences

Article

Content-Based and Cognitive-Linguistic Analysis of Cell Membrane Biology: Educational Reconstruction of Scientific Conceptions

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Abstract: By means of their pivotal role in the outbreak of a variety of diseases, such as, recently, COVID-19, the molecular aspects of cell membrane function have gained considerable attention from researchers in recent decades. The resulting information explosion and the growing interdisciplinary character of cell biology seems, however, to not be represented in science classrooms. Hence, there appears to be a gap between what is scientifically known and what is actually taught in classrooms. Framed by the model of educational reconstruction (MER), the aim of our study is therefore to identify scientific core ideas of cell membrane biology from an educational point of view. This is achieved by conducting qualitative content analysis of relevant cell biology literature. By using Conceptual Metaphor as a theory of understanding, we additionally illuminate the experiential grounding of scientific conceptions. Our results propose that cell membrane biology can be structured into three core ideas, comprising *compartmentalisation*, *physical and chemical properties*, and *multicellular coordination* interrelated by evolution as a key aspect. Our results show that scientists conceive these ideas metaphorically. Embodied part-whole relations seem, for example, to lay the grounds for their understanding of biological function. The outcomes of the study may inform future cell membrane teaching.

Keywords: science education; cell membranes; conceptual metaphor; model of educational reconstruction; scientific clarification; molecular life sciences

1. Introduction

In order to successfully plan and accomplish fruitful teaching interventions, it is important for educators to have knowledge about the scientific content and methods in question [1]. However, increasing interdisciplinarity and the general information explosion that is connected to the molecular aspects of cell biology can make this a challenging task for educators [2–4]. Cell membrane malfunctioning plays a crucial role in the outbreak of a number of human diseases, such as many types of cancer, AIDS, and recently COVID-19. Investigating the structure and function of membrane components has, therefore, received much attention [5–8]. However, although cell (membrane) biology is part of the biology curriculum at upper secondary schools (high school, K-12) in Norway, there seems to be little focus on mediating cell membrane function in the context of underlying molecular aspects. Hence, there appears to be a gap between science content and what is actually taught in schools [3].

Framed by the Model of Educational Reconstruction (MER) [9], we do not understand science content as taken for granted for the purpose of instruction, but rather understand that it must get carefully reconstructed for teaching. This is achieved by a recursive process based on three components: I) the clarification of science content and scientists' conceptions, II) the investigation of students' conceptions, III) and the design and evaluation of learning environments. With the aim to make rather abstract science content more accessible for education by identifying scientific core ideas of cell membrane biology, this study is placed within the clarification of science content.

To identify scientific core ideas, we conducted qualitative content analysis [10] of relevant recent cell biology literature, such as college biology textbooks such as *Campbell Biology* [11] and Alberts' *Molecular Biology of the Cell*, and *Essential Cell Biology* [12,13], other relevant scientific literature in this biological field [5–8,14–20], but also historical research papers [21,22]. In the realm of moderate constructivism and Conceptual Metaphor Theory (CMT) [23,24], we understand science content to be constituted of scientists' conceptions, individual matters of thought, and these to be grounded in embodied results of lifeworld experiences. To understand the experiential grounding of scientists' conceptions we conducted a cognitive-linguistic analysis of traits of their written language as a window into these thoughts. CMT has proven fruitful to understand how scientists actually conceive abstract scientific concepts which lie beneath our conscious awareness [25]. This can be fruitful in the further course of reconstructing science content for teaching by means of illuminating potential learning barriers.

2. Conceptual Framework

2.1. The Contributions of the Model of Educational Reconstruction (MER) for Identifying and Understanding the Scientific Core Ideas of Cell Membrane Biology

The Model of Educational Reconstruction (MER), being greatly influenced by moderate constructivism [26] and conceptual change [27], emphasizes that science content has to be carefully *reconstructed* for instruction. This is achieved by equally taking into account both scientists' and students' perspectives. With that, the model stands with one foot in the scientific discipline and the other in education [9,28]. Predominantly in a German-speaking research community, the MER has proven fruitful for the reconstruction of numerous crucial, from a teaching point of view rather difficult subjects of science education including the concept of energy [29], evolution [30], plant nutrition [31], climate change [32] and cell division [33]. Given the importance of cell membrane biology in science classrooms at (Norwegian) upper secondary schools, and the reported challenges students meet in cell biology in general [33–36], we understand the MER as a suitable framework for this study. To condense, and thereby make scientific content on cell membrane biology more accessible for teaching, is also justified given the rising flood of scientific information due to its impact on our future health. The importance of understanding the molecular aspects of cell biology has, in this regard, been unhappily illustrated by the ongoing pandemic COVID-19, AIDS or increasing rates of certain cancer types.

The MER has three major components that are strongly connected with each other: (I) the clarification of science content, (II) the examination of student conceptions with regard to the topic of interest, and (II) the design and evaluation of learning environments [9,33]. The clarification of science content includes two closely linked processes: the *clarification of subject matter*, and *the analysis of educational significance*. By deriving the scientific core ideas of cell membrane biology, our study provides evidence within the MER's component of the clarification of science content. Thereby, we follow the MER's idea to critically analyse science content from the viewpoint of education. Therefore, we not only scrutinise science content itself, but also scientists' views of the nature of science, and the development of scientific processes by drawing on historical research articles. In the course of this, we also illuminate linguistic expressions which, although not impeding scientific understanding, can be misleading for learners [9]. The Conceptual Metaphor theory (CMT), which' contributions for this study we present in the next section, provides in this regard arguments for the sources of difficulties linguistic expressions can pose for learners.

2.2. Contributions of Conceptual Metaphor Theory for Cognitive-linguistic Analysis

In science education research [25,31,33,35] the Conceptual Metaphor Theory (CMT) [23,24] has proven to be a fruitful tool for the interpretation of conceptions by shedding light on their genesis. Informed by philosophy [37], cognitive linguistics and neuroscience [38–40]), it emphasizes that human cognition is based on sensory-motor experiences like our moving body in space or our experience with objects of different shapes. One way of conceptualising these experiences is by constructing neuronal-based image schemas [41]. Being grounded in lifeworld experiences, image schemas are also called embodied conceptions: preconceptual structures that lay beneath our conscious awareness and are therefore directly meaningful to us [42]. For example, the *container schema*, a result of our experience with containers of different shapes [41], is one of our most basic schemas for the distinction of inside- and outside matter divided by a barrier [43]. As a result of co-occurring experiences, there also seems to be a certain pattern of image schemas that structure our understanding [42]. For example, the *container schema* appears to frequently co-occur with other schemas, such as the *center-periphery schema*, which enables our mind to distinguish between areas that are or are not at the centre of our "conscious awareness" [41], (p. 20). Image schemas seem to serve as source domains for abstract conceptions we cannot perceive directly. This seems to be accomplished through metaphorical thought and is referred to in a neurobiological context as cross-domain mapping (source domain → target domain) [23]. In other words, the concrete results of our embodied everyday conceptions serve as source domains for the understanding of more abstract target domains in the micro- or macrocosmos [44]. As most scientific concepts are not directly perceivable to us, CMT has become an attractive tool in science education research to understand the experiential grounding of scientists', and particularly students' conceptions for a variety of different subjects [25,31], including cell biology [33]. To shed light on the embodied grounding of students and scientists', respectively, thought has proven fruitful in understanding how learning barriers can arise; for instance, although scientists and students were found to draw on the same source domains to conceptualise climate change, they would map these differently to the target domain and thus achieve a different understanding of climate change [33]. Alternatively, by understanding that students apparently map the *container schema* to cells, educators could understand why learners would conceptualise these as brick-like [35,45], rather than flexible structures, which they are from a scientific viewpoint. Taking these considerations into account, we aim to better understand the genesis of scientists' conceptions of cell membrane biology in this study: to shed light on how scientists actually conceive the abstract concept of cell membrane and how this can be valuable in the further course of reconstructing cell membrane biology for teaching. Following the idea of CMT, we, in this study, understand language as a window into our thoughts. The identification of traits related to (spoken and written) language can thus reveal the embodied source domains our (scientific) understanding is grounded in [46].

It seems, in this regard, that little is known about the embodied grounding of scientists' conceptions related to cell membrane biology. However, as shown above, it seems that scientists often apply the same image schemas as learners, although mapping them differently to a target domain [25] Therefore, we expect to identify similar image schemas to those students' were found to draw on in order to conceptualise (cell) biological concepts. We want to highlight some of these schemas, which we understand to be crucial for their conceptualisation in the following.

It appears that the *container*, and *center-peripheryschema* play a crucial role in students' understanding of cells. Based on the *these* schemas, for example, students were found to understand the nucleus as the most important structure of the cell, which has to be protected by the cytoplasm [35] from "exterior forces" [47]. As a source for biological understanding, the *container schema* also appears often to be applied together with the *source-path goal schema*. These two schemas together result in a more complex schema, also called *container-flow-schema* [32,46]. By means of enabling us to conceptualise the flow between different containers [25,48], students were found to apply these schemas to understand nutrition (uptake of nutrients from the environment into the body/plant) [49]. A schema that is mostly found in conceptions where certain properties of people are transferred to objects, is the *person schema* [46]. For example, in order to conceptualise rather abstract and random substance movement, human behaviour often seems to play a role as a source domain for students' understanding of diffusion: molecules were believed to act deliberately like humans, for example, they would have the inclination to fill space, or water would move in order to equalise concentrations [50]. Furthermore, cells were imagined to eat and digest like humans [35]. In this study, the *person* schema is with regard to these findings understood in a broad context, whenever human features or abilities are applied as source domain. Of importance for scientists' understanding of cell membrane biology could also be experiences with changing objects (*transformation schema)* [51], which was found to enable learners' to understand processes of transformation, such as, for example, light that is in the end transformed into carbohydrates [31].

CMT has also proven conducive in terms of scrutinising linguistic expressions applied to communicate scientific concepts for the purpose of education. As scientific termini very often are metaphorical expressions, the search for the experiential source domain of these can be fruitful in terms of understanding that, often, these lead to associations differing significantly from what they are meant to convey scientifically. For example, the scientific term *cell division* puts stress on the lifeworld experience of division; In its everyday meaning, it refers to a decrease in number. Hence, learners are impeded to understand chromosome duplication as a prerequisite for cell division [33]. On the other hand, particularly concerning the molecular life sciences, it seems that many termini, such as, for example, *gene expression,* lack any lifeworld experience, and hence everyday meaning [2]. This lack of a source domain subsequently makes the conceptualisation of *gene expression* difficult to achieve. As a consequence for instruction, it therefore seems fruitful to not only apply scientific termini, and other linguistic expressions, uncritically, but reflect on the associations these do or do not convey [45]. In this respect, many expressions, for example, anthropomorphisms (human characteristics) and teleological expressions (purposes, and intention) [52,53] can in fact also be beneficial for learning. For example, when learners are helped to critically reflect upon their meaning. For the scientific rather abstract aspect of equilibrium (see also next section), Kattmann (2007) [53] suggests that metaphors such as "movement" or "interaction" can indeed be promotive for learning as they can function as an adequate bridge between our experience with balance, and the scientific concept of equilibrium.

As anthropomorphisms, and teleological expressions seem to play a crucial role in students' and scientists' understanding of the molecular life sciences [2], we give these particular attention in the course of scrutinising linguistic expressions in this study.

2.3. Status quo of Cell-Biology Research in Science Education

To our knowledge, there are no studies illuminating the core content of cell membrane biology in the framework of the MER. However, there are a few studies that apply different approaches in the context of discussing this topic in a teaching context. We therefore find it relevant to include their considerations in our study. For example, in their empirical study on how to design fruitful visualizations for the teaching of transport mechanisms across cell membranes, Rundgren and Tibell (2010) [50] mention the following features as critical: (1) the dynamic bilayer architecture of the cell membrane which is shaped by its different components, (2) the barrier function that separates the "interior of the cell from its surrounding environment" (p.233) and (3) the chemical features behind membrane semi-permeability and its effect on substance transport.

In other studies, [3] *compartmentalisation across membranes* connected to *equilibrium* as "key concept" [3] (p.15) is suggested to be central to the discipline of molecular life sciences. The cell membranes' central role in maintaining equilibrium, which is crucial for a number of biological phenomena, such as the production of ATP (adenosine triphosphate), is also stressed by others [54]. Other aspects suggested [3] to be connected to the key concept of *equilibrium* are, for example, *information and communication* through *signaling,* a*queous environments* by means of *buffering and solubility*, *regulation* through *transport binding, and the complexity of molecular structure* in terms of *shape, and polarity.* By means of the interdisciplinary character of molecular life sciences, existing studies [2,55] stress the need to combine aspects of chemistry and biology with other subjects, such as mathematics and physics. Following this idea, others [56] demand not to teach diffusion and osmosis for their own sake (which in fact can be an interpretation of K-12 biology curricula in Norway) but in a broader context.

Framed by the MER and the CMT, the idea of this study is to identify core ideas of scientific conceptions of cell membrane biology from relevant literature in the field. Our aim is not to give an exact scope of the existing literature (which would be impossible), but to condense it from an educational point of view. In the course of this, we want to shed light on the embodied grounding of scientists' conceptions in order to illuminate potential learning barriers.

Based on these considerations, we address the following research questions:

- What core ideas of scientists' conceptions on cell membranes can be identified from literature on cell biology?
- What is the embodied grounding of these conceptions?

3. Methods

In order to identify and understand core ideas of cell membrane biology, we applied Qualitative Content Analysis [10] (QCA) and a cognitive-linguistic analysis framed by the CMT [23,24] to relevant science literature on cell membrane biology.

3.1. Data collection

The global 9th edition of *Campbell biology* [11], more specifically chapter 7 and parts of chapter 6 and 42, functioned as a primary source for the identification of relevant science content. We deliberately chose to consult this educational textbook rather than a pure science textbook as it is widely used as standard literature in biology courses at universities worldwide and is written by scientists who place a strong emphasis on scientific correctness and educational focus at the same time. However, due to validity issues, particularly with respect to more recent findings in the field of cell and molecular biology, we also consulted other relevant literature such as college textbooks with a particular focus on cell biology [12,13] and recent cell biology literature selected based on their focus on membrane structure and function [5–8,14–20].

3.2. Analysis

Following the steps of the QCA [10], we first selected, and then condensed relevant text passages based on their content [57]. A further interpretation was achieved by means of content and cognitive linguistic aspects [24,51,58]. Thereby, we focused on the identification of image schemas, and analysis of linguistic expressions. A description of image schemas in a large body of science education and philosophy literature [41,44,59–62] thereby functioned as source for their identification in the text. To identify these, we focused on semantical structures such as prepositions, postpositions, verbs, body-part-metaphors, cases and morphemes. For example, propositions such as *into* or *in* are usually indicators of the *container* schema.

Linguistic expressions that we, in the course of this analysis, found to be crucial for the communication of cell biology, were furthermore scrutinised critically on their everyday meaning. We did this by consulting the Anglophone online dictionary LEXICO (2019) [63]. In order to reduce our own "blindness" towards common scientific termini or sayings by means of our own background as scientists, and in order to reduce our individual subjectivity, we worked independently and compared our findings carefully.

An illustration of how we conducted the cognitive-linguistic analysis is shown in Table 1 below. The context between identified image schema (source domain), respective semantic text structure (proposition, metaphor, etc.), and target domain is illustrated by highlighting these in a particular, unifying colour**.** Furthermore, the everyday meaning of applied linguistic expressions is shown.

Table 1. Exemplary illustration of how image schemas (source domains) were identified and assigned to target domains.

Text passage	**Explanation**	**Source Domain (Image Schemas)**	**Target Domain**	**Everyday Meaning of Linguistic Expressions [63]**
"The plasma membrane is the **edge of life**, the **boundary** that **separates** the living cell from its **surroundings**". "It **controls traffic** ***into and out*** of the cell it **surrounds**"	The prepositions *into* and *out* express movement of something separated by a barrier. Hence the goal of this is located inside, and outside, the cell. The embodied CONTAINER schema seems here applied together with the SOURCE-PATH-GOAL schema in order to understand the abstract plasma membrane metaphorically as a barrier between two environments. At the same time the PERSON schema seems to serve as the basis for the metaphorical understanding of plasma membranes as "controlling" guards.	container source-path-goal (container-flow) person	The function and task of the plasma membrane (PM) as a barrier and gatekeeper between the cell and its surrounding	Edge: *the outside limit of an object* Boundary: *A line which marks the limits of an area; a dividing line*

The strengths of qualitative content analysis are its systematic procedure and rule-governedness, which is meant to increase intersubjective verifiability and "measure itself against quality criteria and inter-coder reliability" [10]. Nevertheless, an individual interpreter's idiosyncrasies will always be involved [64]. Therefore, two researchers were working independently. Through a subsequent alignment of their findings, we aimed to reduce these idiosyncrasies.

4. Results

We applied Qualitative Content Analysis [10] (QCA), and a cognitive-linguistic analysis [23,24] to define scientists' core ideas of cell membrane biology and the embodied conceptions these are grounded in. As a result, we identified three crucial core ideas of scientists' conceptions. These are presented in Section 4.1. Furthermore, we found scientists' conceptions to be grounded in a variety of image schemas. These are presented in Section 4.2 The context between core idea, the respective underlying image schemas, and anchor examples from the text is shown in the Tables 2–4 in Section 4.2. Each core idea has its own table. The results of the critical scrutiny of linguistic expressions we found to be crucial for the communication of cell membrane biology are presented in 4.3 and summarised in Table 5.

4.1. Scientific Core Ideas of Cell Membrane Biology

In the following, we present the identified three core ideas of cell membrane biology. These are:

1. Cell membranes allow life to exist by enabling compartmentalisation;
2. Chemical and physical properties allow for the biological function of cell membranes;
3. Cell membranes are key factors for intercellular coordination in multicellular organisms.

In the following, each of the identified core ideas are described in depth.

4.1.1. Cell Membranes Allow Life to Exist by Enabling Compartmentalisation

Scientists seem to understand biological membranes as boundaries that allow for compartmentalisation into cells, respectively, organelles (eukaryotes), and thus the creation of distinct environments [11]. By means of at the same time enabling the discrimination of substance exchange between these environments, these compartments can still maintain homeostasis. Scientists understand that this compartmentalisation was crucial in the course of the formation of life.

Therefore, they reason that the formation of membranes—the spontaneous assembly of amphiphilic lipids in aqueous environments—must have occurred early in the course of evolution. Since cells only can arise out of other cells, the cell membrane together with other certain features such as a cytosol, DNA is shared by all organisms.

4.1.2. Chemical and Physical Properties Allow for the Biological Function of Cell Membranes

In 1972, Singer and Nicolson [65] proposed the fluid mosaic model of membrane structure. Scientists understand this to be the result of a number of observations carried out by other researchers [21,22] during the 20th century. Although these did not have adequate tools to study the structure of cell membranes (electron microscopes), they deduced membrane structure by applying their knowledge about chemistry together with observations from previous findings.

Today, although continuously refined, the fluid-mosaic model still lays the ground for scientists' understanding of cell membranes as a dynamic bilayer (particularly lipids move on regular basis in the membrane) made of amphiphilic lipids with attached carbohydrates and attached or embedded proteins. This basic structure is conserved in all organisms. The model explains how membranes are enabled to discriminate in substance exchange by means of the chemical features of their components; thus, it is a "supramolecular structure" with properties that go beyond that of the individual molecules [11] (p.177). The direction of substance transport depends on (electro) chemical forces. As substances have a constant motion, they will subsequently "spread out evenly in available space" [11] (p.178). Therefore, when separated by a permeable membrane, they will move along their gradient from where they are more to where they are less concentrated; an equilibrium is reached when as many molecules cross the membrane in both directions. Thus, oxygen will enter the cell as long as it is consumed, and less concentrated in the cell. Charged substances will additionally follow an electrical force. As long as substances follow their gradient, their transport happens without the expense of energy, and is therefore called passive. This separation of charged molecules represents potential energy. It is actively maintained by the membrane, which subsequently can work as "batteries", storing energy that can be reused for the synthesis of chemical energy (ATP), or transmit nerve signals.

Thus, the membrane's role as barrier serves to keep all cell's components inside where they are needed, and also lays the ground for the establishment of distinct environments that can carry out different biochemical reactions. Its role as gatekeeper on the other hand guarantees the maintenance of homeostasis by enabling continuous supply, and waste of crucial substances (O_2 and CO_2), while it lays the ground for the regulation of others (such as e.g., ions),

4.1.3. Cell Membranes are Key Factors for Intercellular Coordination in Multicellular Organisms

Scientists put stress on the variation of membrane components. For example, different species are found to have different membrane lipid composition as an evolutionary adaptation to temperatures in extreme environments (appropriate membrane fluidity is maintained by the ratio of saturated vs. unsaturated hydrocarbons). A difference in protein composition, on the other hand, results in membranes carrying out different functions in species and cell types. It is particularly protein composition that differs human membranes from these of prokaryotic cells. The information for different membrane compositions, as with all other cellular features, is stored in a cell's DNA. In multicellular organisms, with all cells sharing the same genome, it is the modification of gene expression that results in different cell types.

Scientists picture cells to be functional parts of the body that, together with their secretions (extracellular matrix, interstitial fluid) and according to their specialisation, assemble into tissues. Different tissues subsequently build organs, which build organ systems (such as, e.g., the respiratory system) Cell–cell recognition, carried out by membrane carbohydrates usually attached to proteins, enables cells to distinguish one type of neighboring cell from another, and with this, also reject foreign cells, such as viruses.

Human, and other higher animals' tissues, are characterised by protein connections (junctions) between cells in order to hold these together; this also allows substance exchange between them [12].

As in multicellular organisms, the majority of cells do not have direct contact with the external environment, but, with each other and the surrounding liquid, they depend on sophisticated transport systems in order to ensure nutrient uptake and waste disposal. It also means that it is particularly in these internal tissue environments that homeostasis, a steady state of chemical and physical conditions, must be maintained. This happens by means of signaling pathways between cells: specific membrane proteins (receptors) receive messages, such as, for example, growth factors (also proteins) from other cells. These signals then get step-by-step transmitted to their final destination (e.g., the nucleus) inside of the cell where ultimately a cellular response is triggered (e.g., different gene expression leading to proliferation). Through this mechanism, cells can change their behaviour in response to their respective internal environment. Disruptions in these pathways can therefore cause malfunctions, such as the uncontrolled proliferation of cells, which is one of the hallmarks of cancer. Receptors, however, do not only respond to intercellular messengers, but can, involuntary, also be the targets of foreign intruders, such as viruses, for example, the now well-known SARS-CoV-2. Some cell types, such as, for example, lung cells, express a particular receptor that gets used by the virus as a binding site in order to enter the cell. Severe symptoms of COVID-19 patients are therefore connected to distress in the respiratory system. Consequently, understanding structure and function membrane proteins (genomics, and proteomics) has gained much focus in research communities as they can be promising targets for drug development. In the particular case of COVID-19, specific receptor blockage is hoped to potentially prevent the entry of the virus. As a response to stimuli, membrane composition itself can also be affected (for example, by means of changing receptor density). The constant intake of substances such as nicotine, leads, for example, to an increase in nicotine receptors in brain cells. Thus, a constant high supply of nicotine is needed in order to guarantee the desired effect. Membranes, the components of which are continuously manufactured in the golgi-apparatus, and endoplasmatic reticulum (in eukaryotic cells) are therefore highly dynamic constructs enabled to adapt to environmental changes.

4.2. Different Source Domains together Structure Core Ideas on Cell Membrane Biology

The results of the cognitive-linguistic analysis show that scientific core ideas on cell membrane biology are based on embodied conceptions. We could mainly identify variations of the *container*, *path*, and *person schema*. As an example, we found the *path* schema with its varying experiential source domains of horizontal movement (*source-path goal*), building the grounding for scientists' conceptualisation of, amongst others, temporal aspects, such as, for example, evolution. On the other hand, did we find schemas connected to experiences with human vertical "self-motion", such as walking, running, or jumping [66]; to lay the ground for scientists' understanding of random events, such as substance movement. Bodily movement and the encounter with "physical forces that push and pull us" [41]; (*force schemas*, such as *enablement* or *blockage* [41,47]) appear to serve as experiential source domain for scientists' conceptualisation of, for example, energy consuming processes (e.g., substance movement against their concentration gradient). The *person schema* appears to be a result of a variety of experiences, such as, e.g., human intentional behaviour, by scientists, for example applied to conceptualise the membrane's gatekeeper function.

It seems that co-occurring experiences with part–whole relations *(component/integral-object schema)*, and the flow between objects (*source-path goal, container*) serve as source domain to amongst others understand cell membrane function as a result of its structure.

In the following tables (2–4), we show the context between each scientific core idea with its respective image schemas (e.g., *container*). With respect to the outlined results above, we also show what we identified to be the experiential source domain (e.g., object) of the respective image schemas and what we understood to be their target domain (e.g., the plasma membrane as outer boundary). Selected text passages from the literature used for data collection [11,18] are meant to serve as anchor examples to illustrate the respective image schemas and content.

Table 2. Relationship between the identified scientific core idea that *cell membranes allow life to exist by enabling compartmentalisation*, embodied grounding, and anchor examples from the text.

Core Idea	Image Schema	Experiential Grounding (Source Domain)	Target Domain	(Anchor Examples [11])
Cell membranes allow life to exist by enabling compartmentalisation	*container*	Objects	The plasma membrane as outer boundary	"The plasma membrane is the edge of life, the boundary that separates the living cell from its surroundings".
	person *container-flow*	Human characteristics	The plasma membrane as facilitator for discrimination of substance exchange	"the plasma membrane controls traffic into and out of the cell it surrounds".
	path *-source-path-goal* *-cycle* *-process* *container-flow* *container*	Directional bodily movement/objects	The formation of membranes as prerequisite for the evolution of life	"One of the earliest episodes in the evolution of life may have been the formation of a membrane that enclosed a solution different from the surrounding."
	transformation	Objects	The translation of genetic information into proteins	"..a gene that codes for an immune cell-surface protein called CCR5".

Table 3. Relationship between the identified scientific core idea that *chemical and physical properties allow for the biological function of cell membranes*, embodied grounding, and anchor examples from the text.

Core Idea	Image Schema	Experiential Grounding (Source Domain)	Target Domain	(Anchor Examples [11])
Chemical and physical properties allow for the biological function of cell membranes	*person* *container-flow*	Directional bodily movement/objects Human characteristics	Cells' need for nutrients, and their transport into, and out of cells	"The resources that animal cells require, such as nutrients and oxygen (O_2), enter the cytoplasm by crossing the plasma membrane, metabolic by-products, such as carbon dioxide (CO_2), exit the cell by crossing the same membrane".
	component/integral-object	Objects	Membrane function as a result of the interplay of its different components	"Phospholipids form the main fabric of the membrane, but proteins determine most of the membrane's functions".
	locomotion *container*	Non directional movement Objects	Random substance movement	.."the movement of molecules of any substance so that they spread out evenly into the available space. Each molecule moves randomly"
	person *force (enablement)* *container*	Human characteristics Bodily movement Objects	Active transport	"To pump a solute across a membrane against its gradient requires work; the cell must expend energy".
	force *process* *component/ integral- object*	Directional bodily movement/objects	The process of developing a scientific model	The acceptance or rejection of a model depends on how well it fits observations and explains experimental results.

Table 4. Relationship between the identified scientific core idea that *cell membranes are key factors for intercellular in multicellular organisms,* embodied grounding, and anchor examples from the text.

Core Idea	Image Schema	Experiential Grounding (Source Domain)	Target Domain	Anchor Examples [11,18]
Cell membranes are key factors for intercellular coordination in multicellular organisms	*person* *force* *(blockage)* *container*	Directional bodily movement/objects Human characteristics	Different cell types have different membrane protein composition	"Over time we isolated and characterized more and more different cell types on the basis of the proteins they express on their cell membrane".
	person *contact*	Human characteristics	Membrane carbohydrates' role in cell-cell recognition	"Cell-cell recognition, a cell's ability to distinguish one type of neighboring cell from another, is crucial to the functioning of an organism."
	balance *container-flow*	Non-directional bodily movement	Balanced substance movement leads to equilibrium	… be a dynamic equilibrium, with as many dye molecules crossing the membrane each second on one direction as in the other".
	transformation	Objects	Protein synthesis	"Comparing their genes with the genes of infected individuals, researchers discovered that resistant individuals have an unusual form of a gene that codes for an immune cell-surface protein called CCR5".
	source path *goal* *container*	Directional bodily movement/objects	Membrane potential as source for energy	"The membrane potential acts like a battery; an energy source that affects the traffic of all charged substances across the membrane".

4.3. The Everyday Meaning of Linguistic Expressions Connected to Cell Membrane Biology often Differs from Their Scientific Meaning

In the course of the cognitive-linguistic analysis, we found that the everyday meaning of many terms we identified as crucial for the communication of cell biology differs from what they are scientifically meant to convey.

To understand the origin of this phenomenon, we categorised these terms into three groups according to their different linguistic background: I) terms with different meaning in everyday life, II) terms with a lack of clarity and precision [67] and III) terms without obvious reference to every life.

The results are shown in Table 5. In the following, we give an exemplary overview of examples belonging to these three groups, respectively.

4.3.1. Terms with a Different Everyday Meaning

Scientists do understand cell membranes metaphorically as barriers (see also 4.1). Thereby, they apply different metaphors, such as *barrier, edge of life, boundaries,* and *compartmentalisation*. By means of the everyday meaning of these terms, this can easily give the association of impermeability, which is significantly different to the scientific one: *barriers* in their everyday meaning refer to *obstacles that prevent movement or access* [63], while *compartments* can be understood as an *area in which something can be seen in isolation from other things* [63]. Furthermore, the term *edge* referring to *the outside limit of an object*, could give the association of a rather negligible cell membrane function, which, in reality, however, seems crucial for a cell's very existence from a scientific viewpoint.

We found scientists to apply a number of anthropomorphisms and teleological expressions in order to illustrate substance movement *(traffic*), cell membrane features (*allow, permit*), as well as the organization of cells in multicellular organisms (*hierarchic*).

Our results show that scientists understand the cell as a functionable part of the body. To denote biological organisation metaphorically as *hierarchic* [11] seems to oppose that conceptualization; it refers to different ranks [63] and creates the scientifically unfavourable understanding of cells having the lowest status.

Traffic in its everyday meaning refers to *vehicles moving on a road* [63]. Traffic is usually of directional character as a result of human's intentional behaviour, and its regulation does not discriminate between vehicles. Therefore, this term could lead to the association that the same accounts for substances; however, an important aspect of substance movement is its unintentional, and usually non-directional, aspect, which results in (electro)chemical forces over the cell membrane.

The mentioned anthropomorphisms by which the cell membrane is attributed, such as *allow* and *permit*, illustrate the membrane as a human that consciously decides what is "permitted" and what may enter or leave the cell. This seems to impede the scientific understanding of substance discrimination as a result of chemical features.

4.3.2. Terms with a Lack of Precision and Clarity

We often found scientists to employ same termini for different concepts (such as *environment* for tissues, and the outer environment*)*, as well as different termini for the same concept (*plasma membrane, cell membrane*). Often, in its everyday meaning, the term environment, refers to the "natural world, as a whole or in a particular geographical area, especially as affected by human activity" [63]. Therefore, this meaning differs significantly from the micro-environment in tissues which refers to neighbouring cells and surrounding interstitial fluid. In this regard, we also noted that what in reality from a chemical sense is a protein, is denoted with a variety of different termini with regard to its biological function, such as *enzymes, hormone, messenger, or receptor*. The everyday meaning of *protein* might in this regard rather be connected to its function as dietary compound. In line with previous findings [67], we found that *plasma membrane, biological membrane, and cell membrane* were applied interchangeably.

4.3.3. Terms Without an Obvious Reference to Every Life

Many scientific termini in the context of cell biology are expressions that lack an everyday meaning, since they are of Latin or Greek origin and/or they are artificially constructed.

For example, when being unaware of their translation, it might not be clear that termini such as *fluid mosaic* or *bilayer (Latin: bi: two)* refer to the arrangement membrane components, while termini as *phospholipid*, *amphiphilic (*Greek*: amphi: on both sides; philos: loving)* or *hydrophilic (Greek: hydro: water)* refer to the chemical features of a molecule being a component of this membrane. This is also the case with the termini *equilibrium (*Latin*: aequi :'equal'; libra 'balance*) and *homeostasis (*Greek*: homoios:like; stasis: stopping),* which play an important role in scientists' understanding of membrane function. Often, scientific termini seem to be constructed artificially by means of the assembly of seemingly distinct source domains, such as *concentration gradient*, *gene expression*, or *fluid mosaic*.

Table 5. Identified linguistic expressions about cell membrane biology with potentially ambiguous meanings.

Scientific Terms	Reasons for ambiguity
barrier, edge of life compartmentalisation environment hierarchy the membrane "allows" and "controls" substance transport is "traffic"	everyday meaning differs from scientific meaning
Amphiphile Bilayer Equilibrium Homeostasis Concentration gradient Gene expression Fluid mosaic	unclear everyday meaning
biological (membrane), cell membrane; plasma membrane receptor, protein, hormone	lack of clarity and precision

5. Discussion

5.1. Scientific Core Ideas of Cell Membrane Biology are Interrelated by the Key Aspect of Evolution

Framed by the Model of Educational Reconstruction's (MER) [9] idea of *scientific clarification*, the present study aimed to identify scientific core ideas of cell membrane biology. This was achieved by applying qualitative content analysis [10,68]. In order to unveil the genesis of the scientists' conceptions, we furthermore performed a cognitive-linguistic analysis framed by the conceptual metaphor theory [23,24]. In the course of this, we also scrutinised the genesis of linguistic expressions we understood as crucial for the conceptualisation of cell membrane biology.

Our results show that cell membrane biology can be structured into three core ideas: 1. cell membranes allow life to exist by enabling compartmentalisation, 2. chemical and physical properties allow for the biological function of cell membranes, and 3. cell membranes are key factors for intercellular coordination in multicellular organisms. These findings are supported by other studies with regard to the key aspects of cell membrane biology [2,3,50,54,69]. Outcomes of the study also indicate that scientists have to employ metaphorical thought in order to conceive these ideas. Thereby, we found that scientists apply linguistic terms and expressions that are often crucial for scientific understanding but can potentially be the source of confusion and misunderstanding in a teaching context.

We understand the identified core ideas to cover multiple phenomena of cell membrane biology. Furthermore, we see the concept of evolution of more complex life forms to be the connecting key aspect that interrelates all three of them. This is illustrated in figure 1 below. This means that, from a scientific viewpoint, the formation of cell membranes has to be understood as the prerequisite for the evolution of different life forms.

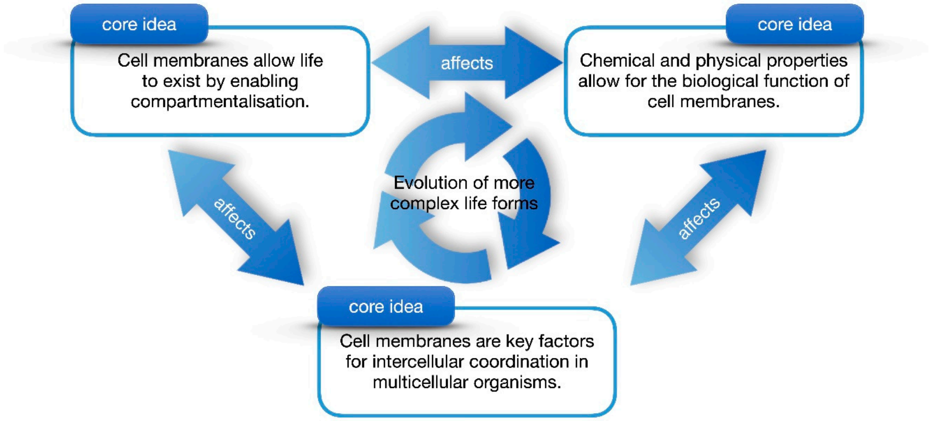

Figure 1. Evolution of more complex life forms as key aspect to interrelate core ideas of cell membrane biology.

Our findings extrapolate Howitt et al. (2008) [3] and Rundgren et al.'s [50] proposal to understand *compartmentalisation* as a core idea of cell membrane biology: it is by the physical separation of distinct environments that these could carry out different biochemical reactions. This laid the grounds for evolution of different life forms from the earliest quite simple prokaryotic organisms to later more complex eukaryotic cells with different membrane enclosed compartments, and subsequently the evolution of complex, multicellular organisms. Our results also support Tibell et al.'s (2010) [2] emphasis on understanding cell membrane function (and much of biological function in general) in light of *chemical and physical properties* and consequently the stress they place on the three-dimensional character of cell membranes. This is also reflected by the historical research into membrane structure in the 20th century, where scientists knew of the existence of cell membranes, however, lacking the necessary equipment to study them, deduced their structure from what they knew about chemistry.

It appears that the crucial function of cell membranes as generators for chemical energy (it is a battery) and the transmission of nerve impulses has to be understood as a result of a combination of physical forces and chemical features. That is, the tendency of molecules to move in space, and the separation of molecules in general, and of opposite charges in particular.

Thereby, membrane proteins play a key role in regulating homeostasis-a steady internal condition-by maintaining equilibrium [3]. In multicellular organisms, this is amongst others maintained by *intercellular coordination*. Different membrane proteins function as a sophisticated regulation system, while membrane carbohydrates function as recognition system. Thus, homeostasis in tissue micro-environments, and subsequently the whole organism, is maintained. By means of regulating their gene expression in order to, for example, increase receptor density, cells are enabled to react upon changes. A breakdown of any of this system's key components can therefore lead to severe malfunctions, such as uncontrolled cell proliferation (cancer), which can only affect multicellular organisms. The variety of different receptors, which is vital for the complex interplay of multicellular cells, also makes these prone to tricky alien intruders, such as coronaviruses, who can misuse specific receptors for their own entry into the cell. For scientists, it seems natural that scientific understanding always is a result of many scientists' contributions. In most cases, it is the hypothesis that best takes into account existing observations that is most likely to be accepted by a community of scientists, such as the fluid-mosaic model of membrane structure having only undergone slight changes since its proposal in 1972 [14].

The results from the cognitive-linguistic analysis [23,24] clearly show that scientists base their understanding of cell membrane biology on embodied conceptions.

It seems that scientists thereby often combine different lifeworld experiences. For example, directional bodily movement (*source-path goal*) with those of objects (*container*) which enables them to conceptualise cell membranes metaphorically as *barriers* [41] and regulating *gatekeepers* of substance exchange between environments (c*ontainer-flow schema)*. Our results, thus, extrapolate Niebert and Gropengießers (2013) [25] finding that the *container-flow schema* is a crucial source to understand the dynamic character of exchange processes between distinct objects (the atmosphere, the cell, and its outer and inner environment, respectively). In other words, our findings indicate that the same embodied structures are applied for the conceptualisation of macroscopic (carbon cycle) and microscopic phenomena. This makes sense as neither are perceivable by us directly (electron microscopic pictures of cell membranes still look like two lines with something in it).

Directional movement appears also to be the experiential source for scientists' understanding of the dynamic character of membranes in regard to the motion of their components (particularly lipids), but also their continuous renewal (e.g., by the integration of membrane proteins from the golgi apparatus). Opposed to directional movement, human movement in a non-directional, vertical sense (like jumping) [66] seems to be an important experiential source domain for scientists' conceptualization of randomness, such as in the case of an individual substance's movement. However, it is the combined experience of directional and non-directional motion that appears to enable scientists to understand some important concepts, such as diffusion and lipid bilayer assembly in aqueous environments. While, on the other hand, their understanding of *forces* seems grounded in individual's movement *against* the directional movement of the population, which requires energy.

Experiences with part–whole relationships (*component/integral-object schema*) seem to be a crucial source domain for scientists' understanding of functionality by means of the interplay of components. As an example, this accounts for their understanding of cell membranes as *supramolecular structures* with properties beyond that of the individual molecules. This conceptualisation is on equal basis to their conceptualisation of cells being functionable parts of the bodies. It did, therefore, not come as a surprise that we did not find the *center periphery* schema to play a role in scientists' understanding, since they understand all parts as equally important for the whole.

Membrane formation, as a prerequisite for the evolution of different life forms, plays a crucial role in scientists' understanding. Based on their experience with continuous, directional bodily movement (*process schema)*, scientists appear to achieve an understanding of temporality [70] and evolution as a still ongoing process.

In line with findings from other studies [2], we found that scientists use experiences with human characteristics and behaviour (*person schema)* by means of anthropomorphisms and teleological expressions to build the source domain for a variety of different concepts. It appears that these often build the source for target domains which were also grounded in experiences with forces (*force* dynamic image schemas), such as, for example, substance movement. Particularly with regard to these different source domains for the same target, we often found scientists' linguistic expressions to be ambiguous. Although this ambiguity is unlikely to affect scientists' understanding, we want to discuss its implication in a teaching context in the next section.

5.2. Implications for Teaching

Our results support existing literature [2,3,50] in clearly showing that the increasing focus on the molecular aspects of cell membrane biology require sound knowledge of several disciplines, such as chemistry and physics, but also an integrative understanding of evolution, genetics and physiology. We, therefore, emphasize that, in order to successfully implement cell membrane biology in K12 classrooms, traditional borders between these disciplines and different biology topics should be transcended. Cell membrane biology in K12 classrooms in Norway seems to mainly focus on specific phenomena, such as diffusion and osmosis. However, our findings extrapolate Marek et al.'s (1994) demand to implement these in a broader context by, for example, putting stress on living system's strive for homeostasis. Moreover, we want to draw attention to the potential of teaching cell membrane biology in the context of well-known phenomena, such as, recently, COVID-19, but also many kinds of other diseases, such as cancer or AIDS. To point out the severe malfunctions that can arise with regard to the breakdown of cell membrane function might be a way towards understanding how it usually regulates homeostasis.

The outcome of the cognitive-linguistic analysis indicates that particularly lifeworld experiences of part–whole relations, distinct types of bodily movement and objects have the potential to serve as adequate source domains for the understanding of cell membrane biology as they enable us to understand its dynamic, three-dimensional character. However, from what is described in literature [35], it appears that learners are more likely to apply distinct experiences as single source domains and map these differently to the target domain; for example, by mapping the *container schema* as sole source domain to cells, it is no wonder that these are conceived as brick-like [35].

The challenge for teaching seems, therefore, to identify and subsequently trigger adequate mappings that take into account scientific core ideas, and students' existing embodied conceptions. In the course of this, we mean that the careful use of language, and the creation of new experiences should play a key role [53,67,71]. Our results extrapolate existing findings [2,53] that many linguistic expressions applied by scientists have the potential to be counterproductive for learning when having an ambiguous meaning. This, we found, can be due to a lack of precision or clarity [67] (e.g., *plasma membrane* vs. *cell membrane*), inducement of inadequate mappings (e.g., the cell membrane *knows*), or no reference to lifeworld experiences (e.g., *fluid mosaic model*). For example, we found a broad specter of anthropomorphisms and teleological expressions to have an opposed meaning to what they are meant to convey scientifically [33]. By, for example, denoting cell membranes as *knowing* and *permitting* there is a danger that learners are triggered to associate these with intentionality and consciousness. If learners are not prompted to reason upon differences between cell membranes and humans [53], this could undermine their scientific understanding (chemical features of the membrane's components are responsible for its function). However, given the abstract structure, and complexity of its function, one is bound to denote cell membrane function and structure metaphorically.

This highlight educators' need to be aware of their students' existing conceptions [27] in order to being able to carefully scrutinise the fruitfulness of linguistic termini applied in science classrooms [33,45]. Thereby, it should be a teachers' task to uncover underlying conceptions and make them accessible for learners [25,31,46]. In the course of this, we stress the importance of creating new experiences that have the potential to prompt learners to reflect upon the meaning of existing embodied conceptions, thereby rethinking the fruitfulness of these. This seems of particular importance in cell biology with regard to many linguistic expressions (such as *fluid mosaic* or *bilayer*) lacking any reference to lifeworld experiences. As proposed by Tibell and Rundgren (2010) [50], a promising approach may be animated visualisations, instead of still images, in terms of highlighting the three-dimensional character of the membrane. These could be combined with other activities where, for example, different part–whole relationships are illustrated.

5.3. Limitations of the Study and Further Research

The Model of Educational Reconstruction (MER) [9] provided a framework for this study. A critical aspect of this model is its recursive process towards the fruitful reconstruction of science content. This includes three closely related steps: (a) a scientific clarification, (b) the examination of student conceptions, and (c) the design and evaluation of learning sequences [9,33]. Guided by the aim to identify scientific core ideas of cell membrane biology, our study was, however, limited to the scientific clarification and was therefore to some degree devoid of the usual recursive process. However, we mean that it has the potential to inform future cell membrane teaching fruitfully by not focusing on science content alone, but also looking at possible ambiguities from the viewpoint of education. This can contribute to the further (re)construction of fruitful learning content for cell membrane teaching. We want to stress that we found the combination of theoretical considerations of the MER, and those of conceptual metaphor [23,24], which has proven to be valuable in similar studies [31,33], to be very fruitful. By understanding the genesis of scientists' understanding, it enabled us to shed light on potential learning barriers in the context of cell membrane teaching.

We finally want to emphasize the need to further investigate into student conceptions on cell membranes and conduct empirical studies on the fruitfulness of our proposed core ideas for cell membrane teaching.

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Article III

Upper secondary students' thinking pathways in cell membrane biology – an evidence-based development and evaluation of learning activities using the Model of Educational Reconstruction

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Abstract

This study reports on the theoretical- and empirical-based design and evaluation of cell membrane biology learning activities within the Model of Educational Reconstruction and experiential realism. First, we designed analogy-based learning activities by considering students' and scientists' conceptions as described in the literature. Secondly, we carried out two video-taped teaching experiments to study students' learning processes when interacting with the learning activities. Interpreting students' conceptual development as thinking pathways enabled us to identify and understand the roots of their learning difficulties. Due to inherent ontological and epistemological presumptions, the students had difficulties in understanding that cell membrane structure determines their two-fold function: to separate and to connect environments in order to maintain living processes. The multiple analogies we employed helped foster conceptual development because they highlighted aspects of the concrete everyday experiences the students already had, but had not thought about. As a result of the learning activities, the students revised their conceptions regarding the terms *barrier*, *gatekeeper* and *environment* and connected these to a more coherent conceptual structure of cell membrane biology. Methods and outcomes of the study may contribute to a better understanding of how this important concept can be brought to science classrooms.

Key Words: Model of Educational Reconstruction, Experiential Realism, Students' Conceptions, Learning Processes, Cell Membrane Biology

Introduction

Understanding cell membrane biology (CMB) is important because it provides insights into the underlying mechanisms of multicellular (mal-)functioning (Watson, 2015). Due to the growing importance of this field for the general public, understanding concepts in the domain of molecular life science is not only critical for scientists, but also citizens (Duncan & Reiser, 2006; Tibell & Rundgren, 2010) to make informed decisions and take part in scientific discussions – as illustrated by the ongoing COVID-19 pandemic.

As described below, the data in this study were gathered in Norway. In the latest Norwegian curriculum, revisions for upper secondary schools (Utdanningsdirektoratet, 2021), both *biology in society* and *biological processes* are emphasised as core ideas of modern biology education. The latter includes knowledge regarding the relationships between cellular structures and functions, such as intercellular communication facilitated by cell membranes.

We see learning as a process where individuals in social discourse develop existing conceptions (Vosniadou, 2014); students' conceptions therefore need to be considered in the design *and* evaluation of learning activities (Duit et al., 2012). Existing studies examining CMB for the purpose of education seem, however, either to take for granted existing science content (Gregers & Suhr Lunde, 2021; Rundgren & Tibell, 2010) or to examine learning only as outcomes from teaching (Marek et al., 1994; Sanger et al., 2001).

Regarding these considerations, this study aims to make CMB more accessible for upper secondary teaching and learning. To achieve this, we employed the Model of Educational Reconstruction (MER) (Duit et al., 2012), and experiential realism (Gropengießer 2003; Lakoff & Johnson, 1980) in our conceptual framework. Combining the MER's moderate constructivist epistemology (Duit, 1996) with ideas from cognitive linguistics has previously proven a powerful approach to link the development of student-orientated learning activities to their evaluation (e.g., Kersting et al., 2018; Messig & Groß, 2018; Riemeier & Gropengießer, 2008).

In this study we drew on the three components of the MER (Figure 1): the investigation of (1) scientists' and (2) students' conceptions by means of reanalysing existing literature, and (3) educational construction to design learning activities. Subsequently, we empirically studied the impact of the learning activities on students' conceptions in two teaching experiments (Komorek & Duit, 2004).

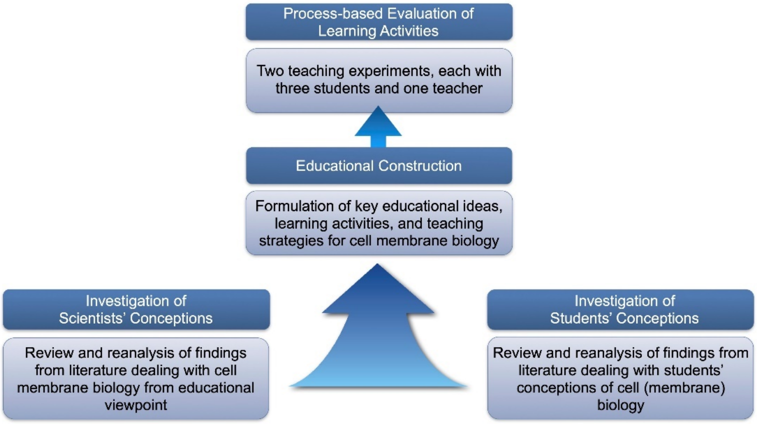

Figure 1. Design of the study according to the Model of Educational Reconstruction.

The research questions guiding our study were:

(1) How can students' and scientists' conceptions as described in the literature be used to design learning activities for CMB?

(2) What characterises students' conceptions while interacting with the designed learning activities?

(3) What implications for CMB teaching and learning can be drawn from (1) and (2)?

Conceptual Framework

Drawing on moderate constructivist ideas, we consider students' conceptions as basic prerequisites rather than obstacles for learning (Duit, 1996; Vosniadou, 2014). According to the perspective of experiential realism (Gropengießer 2003; Lakoff & Johnson, 1980), conceptions are mental models which are grounded in recurring social and bodily experiences become embodied as part of people's intuitions. In that way, conceptions become viable tools to interpret the world in which people live.

Furthermore, we hold the view that thought is imaginative. This means that for concepts which we cannot directly experience (as is the case for most scientific concepts, and also for feelings), we draw on our concrete experiences as source domains to construct understanding of the abstract target (Lakoff & Johnson, 1980). To do this, we employ, amongst other tactics, metaphors and analogies. The latter highlight similarities between concrete source and abstract target domains; however, while analogies make explicit the comparison of structures of two domains (e.g., life is *like* a race), a metaphor (e.g., love is a burning flame) does not: 'Metaphors always have some aspect of surprise; they provoke anomaly' (Duit, 1991, p. 651). In that sense, we understand as analogy everything that explicitly involves comparisons (which also involves examples) (Duit, 1991), whether that is through linguistic expression or other modes of representation (such as visual depictions) (Tang et al., 2014).

Science educators have in recent decades increasingly employed the ideas of cognitive linguistics to analyse students' and scientists' language in order to shed light on the underlying, often implicit source domains to understand potential roots for misunderstandings (Kersting et al., 2018; Messig & Groß, 2018; Niebert & Gropengießer, 2014). Since students and scientists are embedded in specific networks of common experiences in their day-to-day living, they may hold dissimilar conceptions, even though these are based on a common language. Hence, what is meaningful to scientists is often not to students and vice versa (Leach & Scott, 2002).

In this paper, we examine students' and scientists' language by means of focussing on terms (e.g., *barrier*), and concepts (composed of several terms in relation to each other) that students and scientists use when explaining CMB. Concepts get expressed partly through linguistic expressions (e.g., 'cell membranes are barriers'), but also via other modalities, such as diagrams, depictions and models (e.g., the fluid mosaic model) (Gropengießer, 2003).

State of Research into Students' Conceptions of Cell (Membrane) Biology

In line with these considerations, it appears that most student learning difficulties regarding cell biological concepts are rooted in how they construct understanding in the light of their concrete experiences.

Several studies that have investigated students' conceptions of cell biological concepts[1] (Flores et al., 2003; Garvin-Doxas & Klymkowsky, 2008; Lewis & Kattmann, 2004) suggest that differences between the understandings of scientists and students often seem not only rooted at the level of individual conceptions (such as different understandings of the concept of *division*), but also result from differing ontological and epistemological presumptions. While cell biologists seem to understand biological functions in terms of their underlying mechanisms and processes (Johann et al., 2020; Trujillo et al., 2015), students appear to reason teleologically, thinking that structures and processes exist for the purpose of function and are therefore highly efficient (Lewis & Kattmann, 2004; Trommler & Hammann, 2020). Students therefore have difficulties understanding how biological functions relate to underlying chemical structures (Garvin-Doxas & Klymkowsky, 2008; Lewis & Kattmann, 2004) and how the different levels of biological organisation (such as the molecular, cellular, tissue and organismic level) relate to each other (Knippels & Waarlo, 2018).

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[1] In this study we understand the field of genetics, sub-cellular processes (e.g., diffusion, osmosis) and cellular structures and processes (e.g., cell division) as cell biological concepts.

State of Research into Strategies to Foster Learning in Cell Biology

To foster learning of cell biological concepts, it has proven fruitful to offer students suitable new experiences to illustrate new aspects of the experiences students already have. For this purpose, learning with multiple analogies has been shown to be a powerful learning strategy. As an example, to foster students' learning of *cell division*, Riemeier and Gropengießer (2008) let students break a chocolate bar in order to enrich their existing everyday experience of *division* as 'becoming more'. Observing that chocolate breaks into more and *smaller* pieces was apparently a meaningful analogy to the students which enabled them subsequently to construct the understanding that cell division must be followed by a process of cell growth.

Riemeier and Gropengießer (2008) stress, however, in line with other science educators (cf., Duit, 1991; Kersting et al., 2018; Venville & Treagust, 1998), the pitfalls of learning through analogies: namely, when the source domain is inadequate to understand the target, and when the analogy is too abstract for students to understand. The latter can lead to students refuting rather than accepting the new experience because they experience too great a cognitive conflict (Hewson & Hewson, 1984; Vosniadou, 2014). The need to combine multiple analogies for the purpose of learning has therefore been emphasised since a single analogy alone cannot provide all necessary aspects of a source domain. Similarly, it has been argued that not only the combination of analogies but also the use of multiple modalities (such as text, diagrams, etc.) can promote learning in science (Tang et al., 2014).

Methods and Design

In the following, we report on the production and analysis of data within the three MER components. First, we report on the process of constructing key educational ideas and learning activities for CMB, before we report on the empirical evaluation of the learning activities in two teaching experiments.

Educational Construction of Key Ideas and Learning Activities for Cell Membrane Biology

Selection of Literature

To identify and understand students' conceptions of CMB, we examined and reanalysed literature on upper and lower secondary students' conceptions of this concept. The literature mainly concerns diffusion and osmosis (the most extensively researched conceptions in relation to cell membranes) and the molecular structure and function of cells and cell membranes. We therefore examined studies documenting students' conceptions before (Garvin-Doxas & Klymkowsky, 2008; Rundgren et al., 2010), during (Rundgren et al., 2010; Verhoeff et al., 2008) and after teaching (Dreyfus & Jungwirth, 1988, 1989; Flores et al., 2003; Franke & Bogner, 2011; Gregers & Suhr Lunde, 2021; Marek et al., 1994), along with reviews of these studies (Hasni et al., 2016; Riemeier, 2005).

To identify and understand scientists' conceptions of CMB, we explored and reanalysed studies examining CMB content from an educational point of view (Johann et al., 2020; Mil et al., 2016; Rundgren & Tibell, 2010; Trujillo et al., 2015).

Analysis of Literature

The reanalysis was mainly based on metaphor analysis (Lancor, 2014; Moser, 2000; Schmitt, 2017), informed by the ideas of experiential realism (Gropengießer 2003; Lakoff & Johnson, 1980; . That means we systematically screened the literature for original utterances by students and scientists, before we identified metaphorical constructs (such as metaphors, analogies, examples and models) and then reconstructed metaphorical models. We screened the selected texts for, amongst other grammatical terms, verbs and their cases, in order to look for phrases and terminology which could be understood beyond their literal meaning (source area) and transferred to a target domain (Lakoff & Johnson, 1980; Schmitt, 2017). In the course of this, we consulted an anglophone online dictionary (Lexico, n.d.) to decrease our own possible blindness towards terminology that we, as scientists, might not immediately recognise as metaphorical. Meanings and possible source and target domains were discussed in-depth within the author team.

Elaboration of Key Ideas and Design of Learning Activities

Our findings indicate that students often hold conceptions which are inadequate for the scientific understanding of cell membranes, even though they draw on similar source domains as do scientists. These source domains are:

- barriers and their separating feature,
- gatekeepers and their discriminating feature,
- the environment and its surrounding feature.

It appears that due to different ontological and epistemological presumptions, students and scientists draw on different aspects of these source domains (Figure 2) and consequently associate different meanings to terms. When students speak of cell membranes as barriers, they appear to have in mind a *one-dimensional* dividing line which surrounds each cell and separates cells by means of keeping all cells' components (mainly the nucleus) inside. The existing literature refers to students having a 'fried-egg' or 'brick' model of the cell (Clément, 2007; Dreyfus & Jungwirth, 1988).

Scientists, on the other hand, appear to draw on the fluid-mosaic model (Figure 4) for their understanding of CMB. They have in mind *three-dimensional* barriers which, because of their unique molecular make-up, came in the course of evolution to separate insides (water and substances, some crucial for life) and outsides (water and substances) from each other to shape cells *and* organelles (leading to distinct environments that can carry out distinctive biochemical reactions). Thus, scientists have in mind environments as the conditions in which cells thrive and communicate. As a consequence, they think of cell membranes as *gatekeepers* that maintain homeostasis by enabling continuous exchange of substances *and* the regulation of other substances, such as ions involved in processes of energy transfer.

Students, though, often understand cell membranes in terms of decision-making gatekeepers that purposefully discriminate between needed and undesired, dangerous substances in order to protect cells and allow for their survival (much in the way humans intentionally discriminate in substances when they eat).

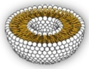
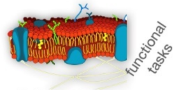
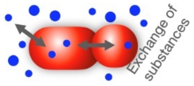
Central Terms used by Scientists and Students	Student Conception	Meaning	Scientific Conception	Meaning
Separation	 **Cell membrane as a single line**	isolation into a single cell ("Brick"-model)	 **Cell membrane as spherical bilayer**	isolation into multiple cells based on lipid bilayer
Protection	 **Cell membrane as a gate keeper that makes decisions**	purposeful selection to guarantee that only needed substances enter and waste leaves ("human nutrition"-model)	 **Cell membrane as a functional layer**	embedded proteins with different functional tasks in the layer that arose during evolution
Environment	 **Cell membrane as a 2D surrounding barrier**	static line that separates the cell from the dangerous environment ("fried egg"-model)	 **Cell membrane as a 3D communicating layer**	dynamic connection between inside and outside ("fluid-mosaic-model")

Figure 2. A comparison of students' and scientists' conceptions of terms which both groups see as key to understanding cell membrane biology.

From this comparison, we conclude that a key educational idea must be that cell membranes allow life to exist (a focus on processes) and be maintained (a focus on molecular mechanisms) by means of both separating from and at the same time dynamically connecting with an environment (other cells and the external environment). In order for students to understand this key idea in terms of their own conceptions, we divided it into six ideas (Table

1)[2] and formulated corresponding learning goals which aimed at introducing the chemical features of amphiphilic lipids and membrane proteins step-by-step.

Table 1. Relationships between the key educational ideas, critical terms to understand CMB and learning goals.

Step-by-step connection between terms to construct concept	**Key educational ideas**	**Learning goals**
Barrier ↕ Gatekeeper ↕ Environment	• Cells membranes (CM) separate cells (or membrane-bound organelles) into individual compartments which each contribute to the function of the cell/tissue by carrying out different tasks. • CM have a unique molecular make-up. Lipids determine the spherical shape of cells, thereby separating them in aquatic environments. • Cells are surrounded by water and/or other cells. • The lipid bilayer is a barrier for hydrophilic, big substances, but allows the continuous passage of small and hydrophobic substances. • Proteins are embedded in the lipid bilayer. They allow for the controlled passage of hydrophilic substances and enable communication with other cells. • Proteins are produced by the cell. Different cell types have different protein composition which changes in response to environmental stimuli.	• Understand that cell membranes are part of cells due to their molecular structure and that there would be no cells without cell membranes. • Understand that a cell membrane is a lipid bilayer with embedded proteins. • Understand that amphiphilic lipids as emulsifiers build a separating layer in water because they spontaneously assemble into a lipid bilayer. • Understand that only small or substances soluble in fat can pass the lipid bilayer. • Understand that proteins can have several functions: provide channels for substances soluble in water and facilitate communication with other cells. • Understand that proteins are produced by cells according to environmental stimuli and therefore are continuously changed.

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[2] Since our literature review suggested that students seem to have few conceptions concerning the movement of substances across cell membranes (sometimes requiring the conversion of energy) or the dynamic interplay between proteins, we saw it necessary to first design learning activities regarding students' epistemological and ontological assumptions before eventually addressing subcellular transport processes and signaling pathways at cell membranes in more detail.

To set into action the key ideas, we designed multiple, mainly analogy-based, learning activities using different modalities (linguistic expressions, chemical structures, etc.) which aimed at highlighting new aspects of the terms *barrier, gatekeeper* and *environment*, which students seemed largely unaware of. Table 2 provides an overview of the learning activities, and the employed learning material, while Figures 3-9 illustrate each learning activity.

Table 2. The learning materials, the learning activities and explanations of the learning activities.

Learning material	**Learning Activity**	**Explanation of learning activity**
Concept cartoon (Figure 3)	1. The function of the cell membrane	Five characters discussing 'What is the function of the cell membrane?' For the design of the statements, students' phraseology according to the literature was used.
Thought experiment	2. House analogy	Rooms in a house as an analogy to cells/organisms
Depictions of chemical structures (Figures 4, 5 and 6)	3. Illustrations of water and phospholipid molecules, fluid mosaic model and liposome structure	Relationships between individual molecules, their chemical features and the fluid mosaic model
Different coloured and shaped candies (Figure 7 and 8)	4. Candy analogy: candies as an analogy for amphiphilic lipids and proteins	Candies with different colours and shapes as analogies to lipids and proteins for students to understand that it is not the shape of these (head and tail) which determines their fundamental function, but their polarity (different colour of the candies)
Glass with water, fluid plant oil and table sugar (Figure 9)	5. Fat analogy: fat droplet in water as an analogy for cell in aqueous environments	When plant oil enters water, it assembles into fat droplets which should be recognised by students as analogous to micelles and cells
Glass with water and table sugar	6. Solubility analogy: behaviour of sugar in water and fat as an analogy for substance transport across cell membranes	Sugar dissolves in water. This should by recognised by students as analogous to the hydrophilic nature of membrane proteins.
Thought experiment	7. Everyday examples: drug addiction and COVID-19	Continuous intake of drugs such as caffeine leads to increased number or receptor proteins. For students to recognise relationship between phenotypic traits and molecular causes.

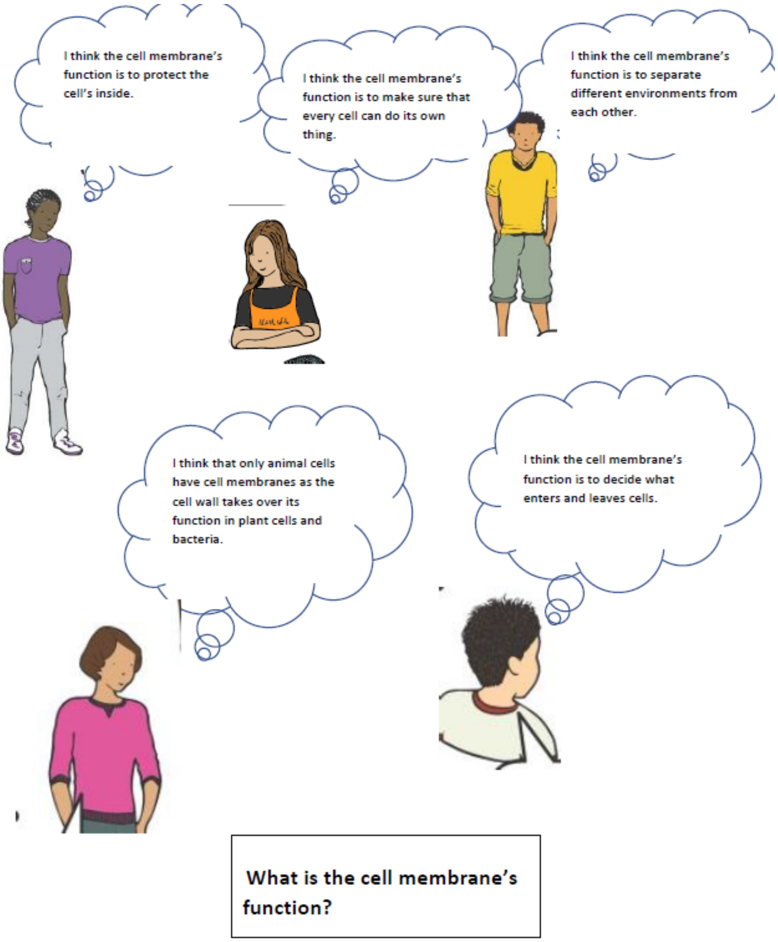

Figure 3. Concept Cartoon to guide students‘ attention to the language they use.

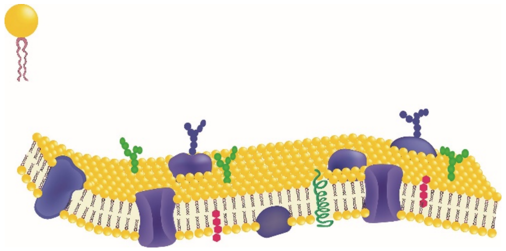

Figure 4. Relationship between amphiphilic lipids and the fluid mosaic model of cell membranes.

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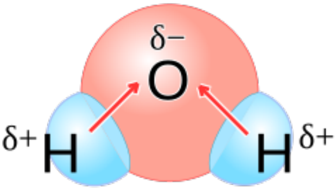

Figure 5. Chemical structure of water molecule to better illustrate the concept of polarity.

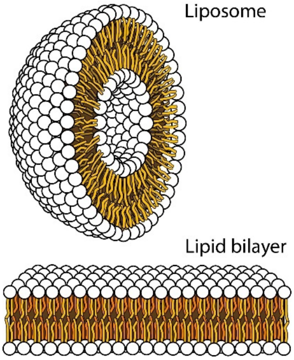

Figure 6. Liposome structure to help visualise that lipid bilayers form spherical cell-like structures.

Figure 7. Different types of candies as analogies for amphiphilic lipids and proteins for students to remodel the fluid mosaic model.

Figure 8. Prototype of candy cell membrane model.

Figure 9. Visualisation of fat droplet in water as an analogy to a liposome.

Evaluation of Learning Activities in Teaching Experiments

To study the impact of the learning activities on students' conceptions, we carried out two teaching experiments (Komorek & Duit, 2004), in each case working with a group of three students and one teacher (the first author functioned as both teacher and researcher, while the second author assisted with the experiments).

Teaching experiments as an empirical method that allow for the combination of an intervention (teaching) with investigational aspects (interview situations and pre-and post-instructional questionnaires). As we conducted the teaching experiments we gained evidence regarding students' individual pre-instructional conceptions, and their collective thinking pathways. The role of the teacher was twofold: to identify students' conceptions by being an active dialogue partner and interviewer (mainly by asking open questions); and to offer learning activities depending on students' (developing) conceptions. The sequence of the learning activities therefore differed slightly in the two groups. The students were assured that the aim of the teaching was not to evaluate their answers, but gain insight into their thoughts.

In addition to increasing the trustworthiness of the results, the pre-instructional questionnaire aimed at increasing students' curiosity for the teaching to come. For this purpose, we designed four open questions according to the elaborated key educational ideas (e.g., 'What do you think is the function of cell membranes?') to invite students to articulate their beliefs. The language employed in the questionnaires, in the same way as during teaching, was mainly based on students' own rather than scientific terminology.

The teaching experiments were conducted in a seminar room at a local Norwegian University within walking distance of the upper secondary school that participating students were attending. They each lasted about 120 minutes and were videotaped to document non-verbal interactions, such as facial expressions and gestures, and help us understand facets of the students' collaborative discourse (Niebert & Gropengießer, 2014).

Participant Selection for Teaching Experiments

Regarding our aim to foster students' collaborative discourse, important criteria for participant selection were that the students had similar previous knowledge regarding CMB, were communicative and motivated, and knew each other in order to create a relaxed atmosphere. Therefore, we picked upper secondary students (in all, two girls and four boys) aged 18-19 who had completed at least one of the two biology courses which are offered at Norwegian upper secondary schools. The final selection decision of the composition of the student groups was taken by their classroom teachers according to the above selection criteria. To participate, all students provided provided informed, written consent.

The teaching experiments took place at the beginning of the spring 2020 outbreak of COVID-19. At that time, the teaching situation at high schools in Norway was rather unclear, which was challenging for both teachers and students.

Analysis of Teaching Experiments

To translate and condense the video recordings into written text and subsequently identify, generalise and interpret students' conceptions, we conducted a stepped process guided by qualitative content analysis (Gropengießer, 2005; Mayring, 2002) and cognitive-linguistic analysis (Lakoff & Johnson, 1980; Moser, 2000; Schmitt, 2017):

- Processing: The transcription of spoken utterances from the video data into written statements (text) and the subsequent condensation of the text.
- Evaluation: The organisation of students' statements into categories (conceptions) by means of assembling similar statements according to content and experiential grounding. By means of explaining students' evolving conceptions through the results of cognitive-linguistics, we further developed the category system.
- Structuring: The finalisation of the categorisation by aligning both groups of students' conceptions to each other.

The whole analytical process was discussed in-depth among the authors in order to minimise subjective mis-readings and opinions. After the analysis, all data cited in this article were carefully translated from Norwegian to English where the utmost attention was given to maintaining, so far as is possible in translation, the meanings of students' utterances, and the nature of their dialogues.

Results

In the following, we give, responding to our second research question, a step-a-step explication of students' identified thinking pathways as a means of indicating their developing conceptions while working with the learning activities. For this purpose, we show, for reasons of space, selected utterances and transcripts from *one* group (Jonathan, Hans and Konrad, all pseudonyms) which illustrate general characteristics typical of both groups.

<u>Cell membranes surround cells and protect their insides from the outside environment by deciding what enters and leaves</u>

Discussing the different statements of the characters in the concept cartoon, Hans, Jonathan and Konrad quickly agreed that the function of cell membranes is to protect cells 'from the outer environment' (Hans), to prevent 'chemicals and other things that are not supposed to come into cells' (Konrad) from entering. Students' rapid agreement about this was unsurprising, given that in the pre-instructional questionnaires they had all written statements which were almost identical to comparable ones in the concept cartoon. Therefore, initially the students found their conceptions confirmed and saw no need to query these.

Apparently, the students drew on two different everyday meanings when thinking of *protection*: either as an act to be carried out actively by 'somebody' (the cell membrane has human features) or as a passive state of being protected (the cell membrane has wall-like features). From the students' point of view, it therefore seemed reasonable that membranes are somewhat rigid (wall-like) and at the same time 'decide' (Jonathan) – a human feature – what 'enters and leaves cells'.

According to this understanding of cell membranes, the students were consequently unsure if plant cells have cell membranes (because they have cell walls). This uncertainty was also fostered by their experiences with school biology textbooks where plant cells look like 'rectangles', so 'you just see cell walls in between cells' (Hans).

Furthermore, the students appeared to think of *environments* as the natural world as opposed to the human world (Lexico, n.d.). As humans tend to experience the environment as hostile, it made sense for the students that cells in the same way as humans *protect* themselves *from* potentially hazardous substances (so that only substances that are needed, such as nutrients, enter cells). According to their everyday experience that substances enter our body (a container-like object) through the mouth, students deduced that substances also enter cells at one 'specific point' in the cell membrane (Jonathan). In accordance with this point of view, the students initially did not find it plausible that cell membranes *separate* different environments from each other because separation for them meant physical restriction: in the same way as humans cannot be physically separated from nutrients, 'cells need oxygen'; therefore, cell membranes 'cannot keep oxygen outside' (Konrad).

Cell membranes separate both cells and organelles, thus contributing to increased organisation

In order for students to reconsider their conception of separation, the teacher requested the students to discuss one of the concept cartoon's statements they hitherto had paid little attention to: that membranes 'make sure that that every cell can do its own thing'. Surprisingly, this resulted in the students immediately constructing the analogy between a (eukaryotic) cell and its organelles: they remembered that (some) organelles, such as mitochondria, also have membranes which make such an organelle 'in principle its own cell'

(Hans). When the teacher asked what the advantage of a cell in a cell might be, Konrad apparently recognised the plausibility of cell membranes having the feature ‘to make sure that cells can make do their own thing’ because ‘it accounts for all types of cells’. Either way if they are cells in cells, ‘all do their own things’ (Konrad) and can therefore ‘collaborate’ (Hans). Since the students had apparently begun to reconsider their everyday concept of separation (as physical restriction), the teacher decided to introduce the *house analogy* as follows:

101 ***Teacher (T)***: So let’s think of it more abstractly. Like, we have a house. And the house has different rooms. And we have five children, and a mother, and a father. And then you have a house which does not have rooms. What advantage might arise with several rooms?

105 ***Konrad***: It gets more **organised**[3] and you **separate** the different ...[4]

106 ***Hans***: ... tasks that must be done.

107 ***Konrad***: Yes. **You do not mix them**. So, you can see it in a cell too. We see the analogy to prokaryotes and eukaryotes. So, you have the five children, and the mother and father who each **have their rooms where they can do their own things.** But in a prokaryotic cell it is less organised.

111 ***Hans***: So, in principle they make own rooms.

112 ***Konrad***: In any case **compartments**.

113 ***T***: So, what is a [eukaryotic] cell in principle?

114 ***Hans***: A house with multiple rooms.

It seemed that the house analogy and the preliminary discussions were fruitful in terms of guiding the students to the anticipated learning goal. The evidence for this was that the

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[3] Terms which are highlighted in bold indicate conceptual development as understood in our study.

[4] Three dots indicate that the students’ talk overlaps one another.

students had started to provide mechanistic explanations by means of employing two new terms which refer to part-whole relationships: *compartments* refer to parts of a bigger whole while *organisation* refers to coordination or structuring of multiple parts (Lexico, n.d.).

Cell membranes are built in a way that allow certain substances to enter and leave

To guide students' attention to the mechanisms for separation, the teacher picked up students' phraseology that cell membranes 'decide' what enters and leaves cells by asking: 'Isn't it like that we borrow the term 'to decide' from the human world when we consciously decide something? How does that work in the cell?'. This led to the following discussion between Jonathan and Konrad:

201 ***Jonathan***: Well, in any case they do not go about thinking if they want to have some water here or there.

203 ***Konrad***: If something is supposed to leave the cell, it must be **edited** in a way that it is **naturally** allowed to come in. The cell membrane is there all the time. So, it is about which substance that comes to enter the cell.

206 ***Jonathan***: Yes, like **it is built in a way** it always allows certain substances to enter.

207 ***Konrad***: Mmm, so, if you want some substances out, it is not the cell membrane that **decides**, but the substance must **be made in a way** it is capable of leaving.

210 ***Jonathan***: Yes, like it is made in a way it can always let certain substances pass, yes.

Jonathan's reaction to the teacher's questions illustrates that when directly confronted with his own phraseology, he experienced some unease. Consequently, he hastened to assure her of his awareness that the way he pictures cells to 'think' was meant metaphorically (lines 201-202). This unease appeared to result in Jonathan and Konrad recognising it as problematic that their explanation was insufficient to explain the mechanisms for substance passage through cell membranes, which triggered an urge to search for more plausible explanations (lines 203-

206). In advance of the dialogue above, the students had remembered that there were ‘ATPases’ in cell membranes. Evidently, the question asked by the teacher fostered a connection to this previous knowledge because the students reasoned that structures somehow must determine functions (lines 206-210). Although the students’ explanations were still shaped by a combination of anthropomorphic (the cell membrane ‘allows’ and the substance is ‘capable’) and teleological (‘the substance must be made in a way’, and comes in ‘naturally’) explanations, what was new was that they had further developed their mechanistic explanations (the cell membrane ‘is built in a way’ and substances are ‘made in a way’). What apparently hampered students in realising the relationship between cell membrane structure and function seems to have been their difficulty in understanding the scientific meanings of terminology connected to cell membrane structure:

211 ***Hans***: If I remember correctly there is a hydrophobic and hydrophilic ...

212 ***Jonathan***: Yes, but are there just lipids on one side of the membrane and something else on the other? I don’t know ..[5]are not lipids hydrophobic or something?

214 ***Konrad***: Yes, I see what you mean with non-polar and …

215 ***Hans***: Yes, but they have two ends, and the one is, for example, a lipid and then there is another one. I think that is phosphorus which is not fat-soluble or what it is.

It appeared that the students at this time of teaching remembered the shape of membrane lipids (see Figure 4) (a hydrophilic head and two hydrophobic fatty tails) which is usually referred to in Norwegian school books, but apparently not the meaning scientists give to this (the molecule is polar). Therefore, the students had difficulties imagining that cell membranes are made up of amphiphilic lipids because they appeared to misunderstand the relationship between lipids and cell membranes (line 212).

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[5] Two dots indicates that the students paused to think.

After this discussion, the teacher introduced learning activities 3 and 4 (see Table 2). At first, it seemed that these activities confused the students by provoking contradictory conceptions; they first became plausible in combination with learning activities 5 and 6. Initially, it seems that the students experienced too great a cognitive conflict with their ontological presumption that the lipid bilayer exists to enable protection and is not the result of the chemical features of amphiphilic lipids. They therefore had difficulties constructing an analogy between the different colours of the candies and the polarity of membrane lipids (instead, they constructed a more evident analogy between the shape of the candies and the shape of lipids in the fluid mosaic model: 'This was one looks like it has a head and a tail[6]' Jonathan). When the teacher asked if they could explain 'Why is it that there is a double and not a single layer of lipids?', the students therefore fell back on their anthropomorphic and teleological explanations: 'I am very sure it only works with two [layers] because cells chose to use two' (Jonathan).

Cells are natural bubbles embedded in water and cell membranes their natural, fatty barriers

Apparently, what helped students to solve their misunderstanding about the significance of chemistry for cell membrane structure was when they *observed* the behaviour of fat in water (learning activity 5), because this enabled them to understand that the lipids in a cell membrane are what they know as 'fats' from their everyday lives. This insight appeared to enable them to make sense of the information that cells are embedded in aqueous environments and that these influence their spherical structure. Evidence for the plausibility of the learning activities was that the students built their own analogies, describing cells as 'natural bubbles' (Hans) with cell membranes as their 'natural barriers' (Hans) which function as 'emulsifiers' (Konrad).

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[6] The heads are meant to represent the polar, hydrophilic part (phosphate group), while the tails represent the non-polar hydrophobic fatty chains of the lipid

Furthermore, the visualisation of fat in water appeared plausible to the students because it helped them to get ‘kind of a 3D understanding’ (Hans) of the cell membrane which they earlier had ‘always thought of as a [one-dimensional] line’ (Jonathan) and apply it to their everyday lives: ‘I did in fact not think of that .. wow. The first time I have thought about that emulsifiers are something I use in reality. Thank you’ (Jonathan).

Indeed, the students refined their concept of cells to their being compartments to enclose molecules such as ‘amino acids’, which would not be there without cell membranes. Hans explained this by constructing the following analogy: ‘You can have all the resources for a cake, but still you don’t have the cake’. Following this mode of thinking, they reconsidered their previous conceptions that plant calls do not have cell membranes.

Cell membranes are made of fats and proteins

As a result of learning activity 6 (sugar dissolves in water, but not in fat), the students extended the analogy to cell membranes: namely, that non-polar substances will be able to cross cell membranes as they are soluble in fat. Since the cell ‘wants’ (polar) glucose inside, the students deduced that the cell membrane also needed proteins to allow polar and ‘specific substances’ to be transported. Prompted by the teacher, the students consequently refined their candy model by including membrane proteins within the lipid bilayer. When the teacher then asked the students to rethink if all cell types have the same cell membrane composition, they reckoned that the protein composition of cell membranes would differ from cell type to cell type because proteins ‘decide’ what gets transported. Students’ utterances showed that in the course of the teaching experiments they would not give up their anthropomorphic and teleological explanations; however, their explanations increasingly included nuances of part-whole relationships at both the subcellular and the tissue level.

Cell membrane proteins enable communication with other cells

In order for the students to become aware of cell membranes' function in enabling connection between cells, the teacher referred to the multitude of cells in human bodies, which the students had referred to earlier, and asked what enabled these cells to be organised in regard to each other.

The students quickly reckoned that cells need to communicate with each other, and that one way to do this is by hormones, for example, testosterone, as 'messengers'. When asked about how this is achieved, the students deduced that it made sense that some cells would produce hormones, while only some other particular cells ('hair cells of the lips or testicle cells', Hans) could respond to these. Apparently, the instructional analogy that most hormones are like keys that fit into particular locks was plausible to the students, because they consequently reckoned that it was likely that only some specific membrane proteins would fit to the hormones.

Communication with other cells and the outer environment influences membrane protein composition

When asked how cells might respond to unusually high amounts of hormones, the students argued that 'cells produce new things' (Hans), which, they remembered, could only happen at the genetic level. Consequently, they reasoned that some messages at cell membranes must be relayed to the DNA in the nucleus which eventually leads to the production of new proteins. This again fostered the thought that the presence of proteins in the cell membrane can vary in response to external messengers. Evidently, the students had, in the course of these dialogues, reconsidered their previous conceptions in which proteins come from outside the body to one in which proteins are conceived of as products of our cells.

Triggered by the teacher's suggestion that external messengers need not necessarily be produced by the body itself, but can be from outside the body (as is the case for nicotine) (learning activity 7), the students constructed the analogy between other physical traits and their subcellular mechanisms, as the following dialogue illustrates:

301 ***Jonathan***: What happens when people smoke, and use snus[7] a lot? After a while they won't experience the feeling of intoxication **anymore**. Why is that?

303 ***Hans****:* Yes, because they have so many proteins.

304 ***Jonathan***: Ah, OK, so they must have ...

305 ***Hans***: ... less effect. The effect **decreases**. And then you want more, and more, and more.

307 ***T:*** That's right. But that also means, of course, the more used you are to a high intake of drugs, the more proteins there are, and the longer it will take to get used to not having them. So, in consequence, the feeling of deprivation will increase. (..)[8]

311 ***Jonathan***: Ohh, so, one gets intoxicated when the receptors are kind of overloaded? (..) And therefore, when you get addicted, you have a large number of receptors, and therefore crave for more nicotine? What a revelation!

The dialogue indicates that the students in the course of teaching had apparently revised their ontological presumption that the existing cell membrane structure is already the best fit and therefore does not change. This is apparent in the way the students employed new terms with a temporal connotation, such as *decrease*, rather than teleological explanations. Apparently what was critical for this change was for the students to understand the role and origin of

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[7] Snus is a tobacco product that is smokeless, and is placed as a moist powder inside the lips. It is very popular among young people in Scandinavia.

[8] (..) means that some passages in the original dialogues are omitted.

proteins. Combined with everyday examples, apparently familiar to the students, namely the change of physical traits (‘feeling of intoxication’), it apparently made sense to them that there needs to be a mechanism (‘more proteins’) responsible for this change.

Jonathan’s exhilarant ‘What a revelation!' at the end of the teaching experiment illustrates students’ increased awareness regarding their own learning process.

Discussion

Framed by the Model of Educational Reconstruction (Duit et al., 2012) and experiential realism (Gropengießer 2003; Lakoff & Johnson, 1980), the aim of this teaching part of this study was to make the relatively abstract concept of CMB more accessible for upper secondary students.

In this regard, we have presented our findings concerning the educational construction of key ideas considering scientists’ *and* students’ conceptions of CMB as described in the literature (Figure 2, Table 1), and indicated how these informed the design of analogy-based learning activities (Table 2, Figures 3-9). Identifying students’ thinking pathways when they interacted with the learning activities (Figure 10) allowed us to generate novel knowledge regarding students’ learning processes of this important scientific concept.

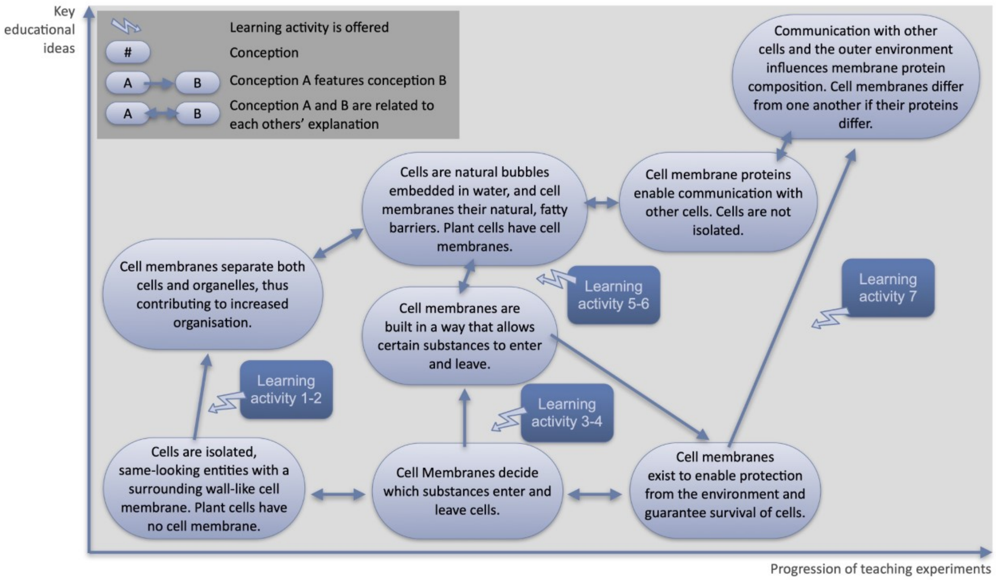

Figure 10. Student conceptions as they develop in the course of the teaching experiments while interacting with the learning activities. Arrows illustrate connections: single arrows illustrate development from one concept to another; double arrows illustrate when concepts are related to one another as explanations for a phenomenon. Adapted from Weitzel and Gropengießer (2009).

In line with findings from other studies exploring the learning processes of complex biological concepts, such as cell division (Riemeier & Gropengießer, 2008) and evolution (Zabel & Gropengießer, 2011), our findings reveal that students can learn CMB when they are given the time and necessary conditions (such as meaningful learning activities and peer interaction) to develop their conceptions step-by-step (cf. Vosniadou, 2014).

Our data suggest that learning CMB is difficult at least in part because students lack direct experiences with this concept – as opposed to perceivable macroscopic phenomena (e.g., the morphology or behaviour of insects) (Bahar et al., 1999; Tibell & Rundgren, 2010). However, since most scientific concepts are beneath students' perceptual awareness, this cannot fully explain the difficulties that students have with this topic. Our findings suggest that the difficulties were due: a) to students' inherent, embodied ontological,epistemological and conceptual presumptions; and b) students' lack of awareness of the limitations of these.

We found that students' inherent assumptions fostered both teleological and anthropomorphic explanations. Initially, the students postulated that cell membranes are one-dimensional barriers which exist for the function of actively protecting the inside of cells by deciding what leaves and enters them (cf. Clément, 2007; Dreyfus & Jungwirth, 1988).

Our findings suggest that these assumptions obscured what we, in line with existing literature (Howitt, 2008; Johann et al., 2020; Rundgren & Tibell, 2010), understand as the key educational idea of CMB: that cell membranes are biochemical barriers which, depending on their particular molecular make-up, allow for the existence and maintenance of living processes because they enable separation (due to the lipid bilayer) into distinct compartments at the same time as they enable the insides of these compartments to be connected (via proteins) to their outsides. For the students it seemed initially rather difficult to understand that the *apparent* perfect structure of cell membranes exists due to chemical features of their component molecules, and that these allow for functions which go beyond what students from their everyday experiences associate with barriers (i.e., static protection).

Other researchers have described comparable roots for learning difficulties in genetics where students were found to view genes as trait-bearing particles (Lewis & Kattmann, 2004) rather than seeing them as chemical structures. Consequently, they did not recognise the need for processes which translate genes to proteins (Garvin-Doxas & Klymkowsky, 2008; Lewis & Kattmann, 2004).

Our data, in common with other researchers' findings (Rundgren & Tibell, 2010), give reason to believe that critical requirements for students to overcome their CMB learning difficulties are for them:

(1) to understand cells (and membrane-bound organelles) in terms of compartments rather than bricks, because this guides their focus to a network of collaborating rather than isolated cells and increases awareness for a 'need' to enable such collaboration;

(2) to extrapolate between one-, two- and three-dimensionality to understand that cell membranes are parts of cells (and not their surrounding wall) and that lipids and proteins collectively constitute cell membranes;

(3) to understand that cells are embedded in aqueous environments which influence their structures. This guides students' focus to the (approximately) spherical shape of many cells ('natural bubbles') and thus gives new meaning to the term barrier as a 'natural' fatty layer;

(4) to understand that membrane proteins enable cell membrane function in terms of facilitating transport and communication among cells;

(5) to understand the origin of membrane proteins (from DNA) in order to increase awareness that cell membranes are dynamic constructs, constantly changing due to dynamic relations with the environment.

Practical Implications

Existing studies suggest animated images as critical learning tools to visualise the dynamic character of cell membranes (Rundgren & Tibell, 2010). Others emphasise, as a strategy for learning molecular genetics in general, making the different levels of biological organisation explicit and switching between these (Duncan & Reiser, 2006; Knippels & Waarlo, 2018).

Similar to Riemeier and Gropengießer's (2008) proposal for the concept of cell division, our study proposes an approach which focuses on making explicit the different everyday meaning of terms that both students and scientists employ to help understand cell membranes (*separate, barrier, environment* and *protection*). To infer learning processes we suggest, in the light of our findings, looking at how to move students from rather passively using terms and concepts to using them more actively. This entails, for example, the generation of, from an educational point of view, meaningful terms (such as *compartment* and *organisation;* transcript lines 105-112) and analogies (e.g., 'natural barrier'), namely the use of 'old words' in a new context (e.g., separation of tasks, transcript lines 105-106) (Haug & Ødegaard; 2014; Lancor, 2014; Lemke, 1990).

Our data build, in this regard, on other researchers' claims (Kersting et al., 2018; Duit; 1991) that multiple analogies (both instructional and self-generated) can be powerful tools to visualise non-tangible relations – as is found in the molecular world of CMB (Tibell & Rundgren, 2010) – as long as they refer to source domains that are adequate from both scientists' *and* students' points of views. Teaching with analogies thus requires that the teacher has sound awareness regarding the conceptions students hold (Driver, 1989; Duit, 1996; Vygotzky, 1978) and how they differ (ontologically, epistemologically and conceptually) from scientists' conceptions (Vosniadou, 2014).

This means that sometimes analogies (and learning materials in general) can be valuably employed at the expense of strict scientific correctness. For example, from a scientific viewpoint it may seem weak to compare cells/organisms to houses because houses are static constructs build by humans. However, for teaching purposes it can be powerful, because it made explicit the usefulness of separated rooms (cells) and their relation to each other (as in tissues). On the other hand, we raise the possibility that the candy material employed in learning activity 4 was suitable because this activity triggered a cognitive conflict among the students, which they found difficult to understand. Although the activity in itself seemed powerful to visualise step-wise how the features of amphiphilic lipids and membrane proteins determine cell membrane structure and function, we wonder whether the material was too abstract for the students to recognise the similarity between the polar character of lipids and the colour of the candies.

In regard to our findings, learning complex concepts in CMB is less about memorising in detail the functions of membrane proteins or studying diffusion and osmosis for their own sake (Marek et al., 1994; Johann et al., 2020), but more about developing existing conceptions step-by-step (Vosniadou, 2014). This does not entail students getting rid of existing conceptions featuring anthropomorphic and teleological explanations, but that they, depending on the context, can make use of mechanistic and process-related explanations.

Our data stress in this regard the importance of emphasising the roles and origins of proteins (Duncan & Reiser, 2007; Verhoeff et al., 2008) in school science curricula in the same way as genes and DNA, because these seem powerful in terms of making evident the relation between ultimate (evolution) and proximate (genes) causes for cell membrane adaptation (change) (Mayr, 2004) as key characteristics of life.

Methodological considerations

Our study confirms that teaching experiments with students can be a conducive way to study learning processes and thus uncover the roots of difficulties when students hold similar conceptions regarding a subject (Komorek & Duit, 2004). In our case, this meant that treating the student groups as ‘communities of practice’ (Lave, 1991) was empirically and theoretically justified.

However, we note some limitations to this method. On the one hand teachers and researchers conducting such experiments must be well informed about students’ conceptions of the given concept, as well as being skilled interviewers (Komorek & Duit, 2004), with the ability to react to students’ utterances at the ‘right’ moment. The researcher conducting the teaching experiments in this study had had sound previous experience of interviewing students regarding this particular topic. Furthermore, the researcher and the participating students had met a few times before the teaching experiments took place at the students' school. This contributed to establishing a relationship of trust between researcher and students which we considered critical regarding our aim for the students to articulate their thoughts honestly (Kvale & Brinkmann, 2009).

In addition, our study was an experimental one conducted with a limited number of students and in small groups rather than in a normal classroom situation where there might be 20-30 students and a lesson would only last 50-60 minutes. That means that our findings only allow us to a certain degree to make informed statements about teaching and students' cell membrane learning in normal classrooms; we also did not investigate long-term-learning.

Conclusion

Cell membrane biology (CMB) has gained increasing scientific attention in recent years, not least as a result of the COVID-19 pandemic. It is important to consider students' conceptions in the design and evaluation of learning activities (Duit et al., 2012; Komorek & Duit, 2002; Vosniadou, 2014) in order to make informed statements regarding how this important concept can be meaningfully communicated for upper secondary education (Utdanningsdirektoratet, 2021).

Identifying students' thinking pathways (Zabel & Gropengießer, 2011) when interacting with learning activities designed within the Model of Educational Reconstruction and experiential realism (Lakoff & Johnson, 1980; Gropengießer, 2006) allowed us to understand the roots of students' learning difficulties and how conceptual development took place. While existing studies suggest animated images to promote learning of CMB (e.g., Rundgren & Tibell, 2010), our study emphasises analogy-based learning activities in order to foster students' conceptual development regarding the terms and statements they use to explain CMB (Duit, 1991; Lakoff & Johnson, 1980). Understanding the terms *barrier, gatekeeper* and *environment* in a new, mechanistic and process-based way enabled the students to relate these to a coherent conception of cell membranes.

The theory, methods and findings of our study may contribute to knowledge as to how students' conceptions can be used to design and evaluate theoretical- and empirical-based learning activities for rather abstract scientific concepts (cf. Kersting et al., 2018; Messig & Groß, 2018; Riemeier, 2008). Whether the learning activities designed in this study can foster CMB learning in real classroom settings will have to be tested in future studies.

Ethical approval.

This study was approved by the Norwegian Centre for Research Data (NSD). The approval number is 339478.

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This thesis consists of three individual articles (sub-studies) and one kappe document. The thesis is divided in two parts: In part I a synthesis of the articles is presented with the overall aim to propose an empirical- and theory-based educational reconstruction of cell membrane biology (CMB) for the upper secondary level. Part II consists of the three articles as the backbone of the thesis. The author recommends to read the articles first.

Article I analytically scrutinises educational textbooks along with recent and historical scientific publications to identify and select core ideas essential for upper secondary CMB education. In *article II* these ideas were used as framework to empirically collect upper secondary students' conceptions (n=9) in individual interviews, and subsequently deduce potential challenges and opportunities for CMB education. As a result, a learning environment consisting of educational core ideas, learning goals and specifically designed teaching tools was constructed. In *article III* teaching experiments with two small groups of upper secondary students were carried out to empirically explore the impact of the learning environment on students' learning processes.

A synthesis of the findings, according to context, prior research, theoretical framework, and methodology as discussed in the kappe, suggests a somewhat different approach to upper secondary CMB learning and teaching than existing ones (mainly for the tertiary level): It emphasises to contextualise CMB within functional processes and mechanisms on the evolutionary and individual organism level. In doing so, it explicitly takes into account the most essential scientific core ideas at stake, such as the *concept of compartmentalisation*, while at the same time addressing students' learning difficulties, which, amongst others, were found rooted in their *lack of concrete experiences*. When following a clear design and scaffolded by cooperative learning environments, multiple analogies, such as two-dimensional depictions and three-dimensional models of cell membrane components, were found useful to promote students' conceptual understanding of CMB.

This thesis contributes with practical and theoretical knowledge with regard to the fruitful implementation of, from a scientific and educational viewpoint, crucial, yet under-researched topic, in a way it becomes meaningful for students' daily life and manageable by teachers.

The present study answers the call for more research which empirically explores the interplay of experiences, conceptions and language to investigate the educational value of abstract areas of science, and provides support for (cell membrane) biology educators facing challenges to organise upper secondary curricula, assess students' conceptual understanding or identify conducive strategies for teaching.

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